Proceedings of the International Conference on Conservation of Stone and Earthen Architectural Heritage

July 2014

Gongju, Republic of Korea

Editors
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The Graduate School of Cultural Heritage
Kongju National University, Republic of Korea
Proceedings of the International Conference on Conservation of Stone and Earthen Architectural Heritage
Published in July, 2014

Organized by ICOMOS-ISCS and Kongju National University
Edited by Chan Hee Lee, Jiyoung Kim and Ran Hee Kim, Kongju National University
ISBN 979-11-953029-0-1

This book is republished by The Graduate School of Cultural Heritage, Kongju National University in Republic of Korea on behalf of Organizing Committees of the International Conference on Conservation of Stone and Earthen Architectural Heritage held in Gongju from 20 to 23 May, 2014. The proceedings in this book were peer-reviewed and accepted by Scientific Committee, and were presented in the conference.

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Proposal to Create an ICOMOS Interdisciplinary Team to Study the Stability of Stone and Earthen Structures of Architectural Heritage

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Abstract

The list of different ways to combine brittle materials like stone and earth in order to build composite constructions is manifold. Because of their stability and in order to simplify the scope of our first steps, we focus this contribution on the specific issues connected with the wall, a mayor structural element. Walls transmit vertical and horizontal loads from the roof to the foundation and are used to cover and shelter rooms from the outdoor weather. The structural behaviour of a composite stone-earth wall depends on several situations. Several questions need to be addressed:

- For vertical loads: is it a stone masonry with mud mortars? Is it a mud wall cladded with stone tiles or covered with stone masonry with mud mortars, is it exposed to incident rain, wind and weather?
- For horizontal or dynamic loads: it is a retaining wall of stone masonry to support a sandy massive soil? Or is it a cover facade of clayey massive soil?

The members of ICOMOS International Scientific Committees (ISC), ISCS and ISCEAH are specialized in the field of stone or earthen constructions It is recommended that both ISCs, form a special interdisciplinary sub-committee to study and develop deeper understanding of the structural behaviour of this large amount of historic constructions. Many objects and sites of the oldest architectural heritage were built with composite material involving the use of the two more or less accessible materials. It is proposed to include also other ISC’s such as ISCARSAH and CIPA in the formation of the interdisciplinary team of the envisaged sub-committee. This contribution presents some case studies from Greece, Peru and other countries with the aim to explain that often apparent stony archaeological sites consist of earthen material as a critical responsible for the structural stability.

Keywords: Heritage, Stone, Earth, Structural study

1. Introduction

Due to its accessibility, the oldest and valuable archaeological findings of the built heritage are constructed with stones or earth. However, the members of the ISCs from ICOMOS, have not yet dedicated to the study of the heritage architecture of stone and earth whose diversity is extensive and complex.

The structures of stone and earth that these two materials have, are from very different characteristics that have been studied separately, further studies are still needed to allow better understanding its overall behavior.

After studying a heritage building to get to deeply know its cultural value, partial or global, it is necessary to define its geometrical and architectonical characteristics, its constituent materials, the cases of deterioration from its materials and structures and to define its current state.

This require studies from the materials to understand its mechanical characteristics in order to define analytical models for the stress distribution under conditions of static and dynamic load (elasticity models, resistance and latest deformations under different stresses, damping and others). A special challenge is that the materials are natural and no industrial where the definition of this characteristics are more imprecise, but the more complex yet is the fact that this materials are combined to work as a unity with new characteristics and its further research and study is still pending.

Circumvented this difficulty will get us closer to perform a diagnosis of its current condition and then an intervention project in line with ecological conditions of each place. From this depends the durability,
maintaining the authenticity, the last two goals of any intervention. Noteworthy was the obvious incompatibility of these goals together. Natural disasters and climate change are accidents which require rethinking their balance. Prevent collapses to not regret irreparable losses. Prevention and preparedness to face risk will dictate settings and alternatives in the future conservation chances.

2. The ability of clay: thixotropy

Among the components of the earth as a building material, there is an active element: clay and other inert components (silt, fine sand and gravel). Contact of water with the clay, even mixed with inert components, increases its volume in contact with water and loses its stability and dry strength. It allows to be mixed with other components, and took form to complement the gaps between the stones. When water evaporates, the mud hardens to reach its dry strength. This physical reversible process makes it possible for the earth to control the displacement of stones and thus improving the stability and strength of the walls which were made of stone only. The walls are the basic structural elements of the structures of brittle materials with low tensile strength. The small particles that make up the clay, have the ability to retain a certain amount of water and maintain cohesion between the earth and stone. Such cohesiveness is variable with the roughness characteristics of the rock.

3. Mixed building techniques of stone and earth

In the previous paragraph was possibly define the most common technique used with stones and earth: The masonry of stone with earthenware mortar there exists many variations inside this technique and it would be important to classify them. But the role of this paper is to just warn about the necessity and importance to perform organized laboratory programs that will answer to unknown mechanical characteristics.

Let us now talk a moment about the material resistance of earth shaping mortars to hold and form masonry walls. Laboratory tests have revealed a series of useful knowledge in the use of earth mortars in this type of techniques. Here are 11 useful assertions for future research:

- The resistance of the masonry walls of stone and earth together depends largely from the quality of the mortars that connects the stones.
- The masonry walls of stone and earth joints normally cracks through the joints or earth mortars in the surfaces between the two materials where the adhesion is less.
- The drying rate of the clay mortar is a very important variable to avoid the cracking of the mortars, diminishing the cohesion and resistance of the clay.
- The clay is an essential component for the resistance of the mortars although the excess of it cracks them. To avoid this it must be balanced the earth components.
- There is laboratory proven field tests that reveals if the presence (quality or quantity) of clay is enough to make good mortars to build (Vargas J. et al, 1984).

Figure 1. Sacred sites architecture, temples. Credits: Authors.
- The straw is a better natural additive to control the cracks in the drying process (Vargas J. et al, 1984)
- The quantity of water in the mortar mix must be minimum to guarantee the activation of the clay particles with a large and efficient paste.
- The paste must guarantee the uniformity of the mixture of components for the earth mortar.
- Increasing thick sand to the mortars of clay soil is another successful form to avoid cracks in the mortar. There are field tests to optimize the mix of each clay soil with thick sand avoiding fissures and increasing the resistance (Vargas J. et al, 1984).
- The lesser thickness of the mortars significantly increase the resistance of the masonry walls. To a lesser thickness the probability of significant imperfections get lower and the resistance of the mortar improves (Blondet M. et al. 2007).
- The elasticity module of the walls depends more in the cohesive quality and resistance of the mortars and its elasticity module than the elasticity module from the stone masonry. It also depends on the forms, porosity and size of the stones or the relation between the resistance areas of each material.

Another common technique is the walls with thick earth cores protected with exterior stones in both sides. In this technique the resistance of the walls depends on the quality of the earth, thus if there is joints with earth mortars between stone and stone, as if there is no joints at all (dry joints). Largely the previous asseverations are also useful for this technique.

It might exists an important variation in the results, if the walls are made compacting the earth from the core by thin layers (150 mm) inside wooden formwork that allow this compaction beside the placement of the stones next to the formwork. It is possible that the humidity of the mix may decrease significantly since the activation of the clay by water exposure is performed with compaction. This variant also may be use lesser amount of clay looking for a decrease in the cracking of the drying process but the cost may fall on the decrease of the resistance. The most efficient way to obtain dry resistance is through the quality and quantity of the clay, the only active component of the soil and not as some times is believe, through more compaction.

![Figure 2](image1.jpg) Delos walls made from Stone and earth. Credits: Authors.

![Figure 3](image2.jpg) Detail of the Stone masonry with earth mortar. Credits: Authors.
In the other side are presented techniques where the core of the earth is from a large volume and the placement of the clay was done relying on megaliths that act as contention walls (Sacsayhuamán Fortress, Cusco) or the contrary, the cores are later covered by fine carved stelae of stone that act as protective facade (Chavin de Huantar, Ancash) or as alternatively facades of small rounded stones, pressed against the earth core (Vichama de Végueta, Lima).

4. Examples of Delos, Greece and Machu Picchu, Peru

In many deposits or archeological sites built with stones and earth, there is a variety of constructive techniques that mix both materials. In general, the sacred zones tend to use megaliths (where earth is no longer useful) and many pieces carefully sculpted. In the Delos island, there can be found one of the most important archeological sites of Greece, where you can appreciate temples made with big stones carefully carved, where no earth mortar was used neither another material. There are traces of metal staples. 600 B.C. In Figure 1, some examples. The most part of the lesser constructions, are made with Stone masonry and earth mortars, forming horizontal rows. In Figure 2-a, you can appreciate an overview and in 2-b, a detail that reveals a stone masonry with a core of earth. Figure 3 shows the earth mortar inside the joints exteriorly washed by the rain.

![Figure 4. Free design that combines sculptures with structural walls. Credits: Authors.](image)

![Figure 5. Natural integrated rocks, sacred rocks, Temple of the Sun and Stone with earth masonry.](image)
In Figure 4, are shown sculptures of stone in the bases of the walls of stone and earth masonry. In the south of America, Machu Picchu, Cusco, without any connection, the Incas built similar walls of stone and earth. Also the sacred parts have megalith walls connected without mortar. Figure 5 shows some stone walls and different earth combinations from walls with dry joints and also big masses of earth.

The fundamental difference between the two cases is that Cusco has an important seismic activity that shifts its preservation concepts. In the year 1650 occurred a big earthquake that destroyed the Hispanic and pre-Hispanic edifications including Machu Picchu. In Figure 6 is shown the seismic destruction of 1650, in the reserve zone without intervention and it can be seen the seismic faults.

![Figure 6](image)

**Figure 6.** Volteo y fallas de corte en los muros, propias de la acción sísmica.

5. Conclusion: the necessity of further interdisciplinary studies for the heritage constructions of stone and earth

The picture shown tries to draw attention to two important subjects in the preservation of historical buildings of stone and earth:

- a) The vulnerability of the heritage constructions of stone and earth depends largely in the vulnerability of the weakest material that is the earth.
- b) The seismic activity complicates even further the mentioned vulnerability of the mix masonry.

Consequently, it is of utmost necessity the constitution of an ICOMOS Interdisciplinary Team to study the stability of stone and earthen structures of architectural heritage.
References


Conservation of Cultural Heritage in Korea

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1. Introduction

The early man first inhabited in the Korean Peninsula approximately half a million years ago. Through this extensive evolution and from Korea's long history, we have gained many precious cultural heritages. They include both tangible and intangible cultural heritages like historical buildings, monuments, tombs, handicrafts and folklore materials etc..

Entering the 20th century, the Korean cultural heritages had been confronted with very sorrowful history. They are the Korea under Japanese Rule period (1910-1945) and the Korean War (1950-1953). Many Korean heritages were distorted, damaged and destroyed severely during these period. After the liberation from colonial rule, the Korean government overhauled the state designated heritages which were selectively designated based on the colonial government's perspective and taste. The first thing Korean government focused on, was to fill up the list by adding missed cultural heritages and historical sites and restore those which were seriously damaged.

Conservation activities and efforts in 1960s and 1970s had served for sites and objects which were excavated during the period. To enhance public awareness and scientific conservation on cultural heritage, the government invested more in nurturing professional workforce and developing relevant technologies and knowledge. Led by some pioneering researchers in the Cultural Properties Bureau, the cultural heritage research department including small scaled conservational team, was created in 1969. Later, the research department was scaled up and became as the National Research Institute of Cultural Heritage (NRICH). In addition, the National Museum of Korea set out a conservation team also in 1975. The NRICH is taking a critical role in the conservation of nationally important historic sites and architectural heritages which they stand outdoors, while the National Museum play a role in conserving movable cultural heritages which they are preserved in the museum.

2. Preservation of cultural heritage

The preservation of Korean cultural and natural heritages has been supported under the auspices of laws such as 'the Cultural Property Protection Act'. According to the Act, cultural property is defined either artificially or naturally by assessing its national and global importance, whether the property possesses high historical, archaeological, artistic, academic and scenic values in terms of tangible properties (buildings, pictures etc.). While with intangible cultural properties (music, craft technique etc.), historical sites (temple sites, shell mounds etc.), scenic places, natural heritages (animals, plants, geological features etc.) and folklore materials(clothes, tools etc.), the degree to which the properties contribute to the understanding of the Korean lifestyle is carefully examined to assess whether they are indispensable.

For the preservation of cultural properties, the Korean government may designate a specific place or monument of high cultural value. These are classified as National Treasures, Treasures, Important Intangible Cultural Properties etc. The local governments may also designate cultural properties that require preservation. Currently, there are 11,962 designated properties which are worth preserving by the central and the local governments. Besides these designated properties, now we have 10 items of the World Heritage, 11 items of the Memory of the World and 16 items of the Intangible Cultural Heritage of Humanity by UNESCO.

And in spite of the prohibition of archaeological excavations in principle, the number tends to increase yearly. In 2013, the authorities permitted approximately 1,676 excavation projects. The rescue excavation which
has been done prior to the construction work, occupies 86%. Furthermore archaeological materials which stand in need of conservation are constantly increasing.

The Cultural Heritage Administration (CHA), which belongs to the Ministry of Culture, Sports and Tourism, is a representative organization of the central government for the preservation of cultural properties. The preservation policies are formulated and carried out on the basis of ‘the Cultural Properties Protection Act’. The purpose of the Act is to promote cultural improvement for the people. This would then contribute to the development of human culture by inheriting, preserving and widely utilizing the national culture.

The Cultural Heritage Committee, composed of the highest authorities in their fields, is the supreme body of the CHA. The Committee deliberates all policies for the preservation, management and utilization of cultural properties.

The National Research Institute of Cultural Heritage (NRICH) has been conducting comprehensive academic studies on Korean cultural heritages. It is also an advisory body to the CHA. The NRICH headquarter is organized in Archaeology Division and 5 others, also it manages 5 regional institutes and 1 Conservation Science Centre. Recently Intangible Heritage Division was newly extended and organized as the National Intangible Heritage Center. There are 3 posts a related conservation and restoration. Conservation Science Division has started in 1975 and Restoration Technology Research Division in 2006. Lastly, Conservation Science Centre launched its responsibilities from 2009.

The main goal of conservation and restoration divisions of NRICH is to study the scientific conservation of cultural materials and to preserve these priceless cultural heritages for the future. The functions include researches for the improvement of conservation methods, analytical work for the examination of objects, measures against bio-deterioration, environmental monitoring, regular inspection of historic monuments and dissemination of conservation knowledge.

3. Conservation of stone objects

Currently as of the end of December 2013, there are 692 designated stone cultural heritages including 79 national treasures, 516 treasures etc. by central government. They are various in types of pagodas, Buddha statues, funerary stupas of Buddhist monk and tombstones, and they are made mostly of granite, but sometimes of marble, sandstone, gneiss, andesite, conglomerate and clay slate. A common point of these stone cultural assets is that they are positioned near stone material production areas.

In addition, because most stone cultural assets are older than a thousand years and stand outdoors they have been weakened and damaged by natural environment such as rain and wind as well as artificial factors such as war, robbery, plunder etc. Currently, representative challenging issues of stone cultural heritage in Korea can be presented as follows

3.1. Seokguram Grotto in Gyeongju (National Treasure No. 24)

The construction of Seokguram Grotto was completed in 774. An artificial stone cave was built using pieces of white granite. The principal statue of Buddha was placed at the center of the cave and a total of 39 images of various Buddhist monks, disciples, and guardian are carved on the surrounding walls. The ceiling in the round-shaped main chamber is exquisitely made with more than 360 pieces of flat stones. Seokguram Grotto is the masterpiece built during the golden age of the Buddhist art in Silla. What makes it stand out further is a perfect combination of architecture, mathematics, geometry, religion and art. Along with Bulguksa Temple, it was jointly registered at the UNESCO as a world cultural heritage in December 1995.

In 1910s, Seokguram Grotto has been extensively repaired by Japanese people and then the waterway for a drainage inside it was blocked, which caused environmental problems. Since 1960, through double-dome was set to compensate the defect, environmentally it still leaves much to be desired for improvement. The conservation of Seokguram Grotto is the extremely hard work we confront in the field of conservation.
3.2. Stone Pagoda at Mireuksa Temple Site, Iksan (National Treasure No. 11)

The pagoda might be built during the King Mu (600-640) at the end of Baekje Era. It is a very valuable cultural treasure as it faithfully shows the transferring process from wooden to stone pagoda. Presently the remaining part is only up to sixth floor, and about half has been crashed. It is very sorry that the crashed part is cemented, but it is the oldest and largest among the remaining stone pagoda.

For this pagoda, dismantling and restoration projects were decided for weathered conditions on cement concrete supported by Japanese people and structural problems. Dismantling started since 2001 and restoration will be completed in 2017.

3.3. Ten-story Stone Pagoda at Gyeongcheonsa Temple Site and Ten-story Stone Pagoda at Wongaksa Temple Site (National Treasure No.86 and No.2)

The Gyeongcheonsa pagoda was erected in the 4th year of the reign of King Chungmok of Goryeo (1348). During the Japanese invasion of Korea, it was taken to Japan, but later returned, and relocated to the Gyeongbokgung Palace in 1960. This is 13 meters high, 10-story pagoda is distinguishing itself from other Goryeo pagodas. This pagoda stands out as one of the finest examples of Korean pagodas.

The Wongaksa temple was founded in 1465, early Joseon Dynasty. This Wongaksa Pagoda is the only one left among stone pagodas from the Joseon. This is 12 meters high, 10-story pagoda and it draws a lot of attention because its shape is so similar to the Gyeongcheonsa Pagoda.

Both of two stone pagodas were unique in that they were made of marble, because the common material of Korean stone pagodas is granite. And they were located in Seoul for years, which were seriously damaged by air pollution. Therefore, in the case of Wongaksa Pagoda, it was covered with protective facility in glass for protection, while Gyeongcheonsa Pagoda was dismantled and relocated at the main hall of National Museum of Korea after broad-scale conservation treatments.

3.4. Three-story Stone Pagoda and Dabotap Pagoda of Bulguksa Temple (National Treasure No.21 and No.22)

The Bulguksa Three-story Pagoda and Dabotap Pagoda are respectively situated in the east and west of the front yard of the temple's main hall. The pagodas seem to have been built in 751 when Bulguksa Temple was freshly remodeled with a large scale. The height of the two is same of 10.4m. The 3-story pagoda does not have any special decoration to be simple. The work looks very settled in any direction of the pagoda due to its excellent balance, and we can feel the simplicity and grandeur from the pagoda.

The Dabotap Pagoda is a masterpiece that the work evidently shows the artistic essence of the Unified Silla in that it has the well-organized structure using squares, octagons, and circles, and in that the length, width and thickness are standardized in every part.

Since its building, the original figure had been preserved properly, but it is very sorry that the 3-story pagoda was damaged by robbers in Sept. of 1966. Afterwards the pagoda was reconstructed in 1966 and in 1973 again. The Dabotap Pagoda was dismantled and repaired by Japanese around 1925, but they didn't leave any record about this fact. These two pagodas have gone through conservation treatments several times due to weathered stone materials and structural instability. The latest conservation for Dabotap Pagoda was conducted in 2009 and Three-story Pagoda has been under the ongoing project for repair since 2013.

3.5. Stupa of State Preceptor Jigwang at Beopcheonsa Temple Site (National Treasure No. 101)

According to an inscription on the stele the stupa was erected around 1085, the year when the monk, Haerin
of Goryeo, passed away. This stupa characterized by an unusual square plan, rich but refined decoration, and outstanding sculptural workmanship. During the Japanese colonial rule of Korea, the stupa was taken from its original location to Japan, later returned to Korea.

This stupa was destroyed from bombing during the Korean War and restored to the present state in 1957. But it has been in danger which was caused by cement mortar used in the past and weathered stone materials. Conservation project will be carried out for this pagoda from 2015.

3.6. Petroglyphs of Bangudae Terrace in Ulju (National Treasure No. 285)

It seems that the stone engravings were made between the end of the Neolithic Age and the Bronze Age. This rock carving on shale is 3m tall and 10m wide. On the surface of the rock, a total of 200 drawings showing 75 kinds of land animals and sea animals and hunting scenes are engraved.

Due to the construction works of Sayeon Dam in 1965, the engraving rock is presently underwater. Since then, the rock carving has sunk under water and exposed to the air repeatedly every half a year. Therefore, it is now in danger from serious abrasion and weathering. But there has been a big conflict between the local authority and the central government and it still remains unsolved. Because one is claiming that first of all, clean drinking water should be supplied for local people and the other is insisting on controlling the water level of that dam.

4. Conclusion

From the middle of the 1970's, concepts on 'conservation science' began to be newly introduced to Korea. The conservation of historical remains require the aid of science for its preservation and this matter came into the limelight since the 1950's with the conservation problem surrounding the Seokguram Grotto. Furthermore, brilliant artifacts have been found from several archaeological excavations of the 1970's. Since the introduction of conservation science we have had much promotion in qualitative and quantitative.

Many Korean cultural properties are still in danger mainly due to natural degradation. Although technology and knowledge on the conservation of cultural properties have increased during the last several decades, yet more cultural properties are endangered today than ever before. Especially the changes in the environment such as air pollution due to rapid industrialization, are among the most serious problems. Other major threats on cultural properties have also arisen from wrong management. These include crimes of treasure hunters, indiscreet or illegal development works by the public institutions and individuals for their own profits. For the moment, we do not have any practical solutions to such problems.

Now the Korean community of cultural heritage has not yet recovered from the deleterious effects of the fire accident of the Sungnyemun Gate and a serious of wrong restoration. It gave us irreparable hurt and also a great value of teaching. The bottom line is that we need to change recognition from a growth-oriented way of thinking to valuing the process and principle. It is, however, important to recognize our duty as a temporary successor that we should preserve cultural heritage and hand over to the next generation.

References

NRICH, 2009, the 40th Anniversary of NRICH, National Research Institute of Cultural Heritage, Daejeon.
Detection of Structural Layers of a Cored Marble Column from the Market Gate of Miletus with Traditional Ultrasonic Tomography and Innovative Phased Array Sonography

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Abstract

In this study ultrasonic computer tomography and sonography are compared in the investigation of a cored marble column. The marble column presents a complex stratigraphy of several layers. Both methods could complementarily detect the layers, although each technique alone would not suffice to characterize changes in mechanical properties at 5 cm depth as well as at 17 cm depth. Further research is needed to merge the performances of both. The development of special transducers and coupling media for ultrasonic computer sonography applications seems to be promising for the field of stone conservation.

Keywords: Ultrasonic velocity tomography, Non-destructive testing, Sonography, Marble, Market Gate of Miletus

1. Introduction

Ultrasonic pulse velocity (UPV) in single measurement points and iteration of ultrasonic velocity data in computer tomography (UCT) are widely used techniques in conservation science to characterize the damage of stone in cultural heritage (a.o. Côte (1989), Simon (2001), Ahmad et al. 2009). Ultrasonic computer sonography (UCS) is commonly used in the clinical diagnostics, however its application to determine cracks, holes, layers or reinforcements in marble is rather new.

In the frame of the joint research project ‘Entwicklung eines Ultraschallgerätes zur Analyse anthropogener Umweltschäden an Denkmälern aus Marmor’ (Development of an ultrasonic device for analyzing man-made environmental damage on marble monuments) funded by the Deutsche Bundesstiftung Umwelt (German Federal Environmental Foundation) an ultrasonic phased array sonograph was developed to study inclusions, reinforcements and cracks in marble structures.

In a first step, the sonographic equipment was developed with adequate transducers and software. In a second step, it was tested on reference marble specimens treated with specific defects/inclusions in the laboratory. In a third step, the equipment was tested on real objects previously investigated by other authors.

The Market Gate of Miletus, a historical façade dated in the 2nd century AD, exhibited in the Pergamon Museum of the National Museums in Berlin, Prussian Cultural Heritage Foundation, represents the former entrance to the state market of Miletus (s. fig. 1). The gate, damaged by an earthquake, was unearthed by Theodor Wiegand and Hubert Knackfuss in 1903 and transported to Berlin from Anatolia. In 1928 and 1929 the gate was re-erected in the Pergamon Museum where it can be seen today (Pfanner et al. 2003). Within the reerection of the façade, the columns were cored and reinforced with iron bars, which have the function of a skeleton. Further materials were used to fill in the gap between the iron bars and the marble cylinder walls of the columns.

In this study UCT and UCS were used to characterize the depth of construction layers forming one column of the Market Gate of Miletus, which was previously investigated by Siegesmund and Ruedrich (2005).
2. Materials and methods

2.1. Marble column

According to Siegesmund and Middendorf (2008) the marble used in the Market Gate of Miletus is characterized by its grey-white color and locally dark grey bands. The marble is coarse-grained with a medium grain size between 1.0 and 1.5 mm and a compressive strength of about 60 MPa (Siegesmund and Middendorf 2008). The case study of this paper is the column of the market gate in fig. 1, specifically a section at the height of 60 cm from the ground level.

![Figure 1. The Market Gate of Miletus in the Pergamon Museum, National Museums in Berlin, Prussian Cultural Heritage Foundation. The investigated column is marked with a rectangle (third column from right on the ground level).](image)

![Figure 2. The UCS$_1$ MHz equipment developed by the Fraunhofer Institute for Biomedical Engineering.](image)

2.2. Ultrasonic computer tomography (UCT$_{46kHz}$)

The UCT$_{46kHz}$ of the tested column was based on the sending and receiving ultrasonic waves from 24 coordinates, which mostly coincide with the measurements made by Siegesmund and Ruedrich (2005). Altogether 276 measurements were performed with a USG 20 (Fa. Krompholz, Geotron-Elektronik, Pirma, Germany) equipped with a 46 kHz piezo ceramic transducer (UPG 46-T) and receiver (UPE-T). By using the RAI-2D iterative algorithm developed by Côte et al. (1995) it was possible to estimate the ultrasonic velocities inside the column and to create a map based on curved beams (s. fig. 5). The curved beams describe the most probable travel paths of the ultrasonic waves inside the material. The parameters for the algorithm are given in table 2. For visualization Surfer 8 by Golden Software was used. Since the measurement depend on various parameters (a.o. contact pressure of the transducers, detectability of the start signal, water saturation) the accuracy of in situ measurements is assumed to be approx. +/- 10%.

![Table 1. Parameters for the RAI-2D algorithm.](image)
2.3. Ultrasonic computer sonography (UCS\textsubscript{1MHz})

The ultrasonic computer sonograph (s. fig. 2) detects reflections of ultrasonic waves on boundaries between two materials with different acoustic impedances. Ultrasonic waves with a 1 MHz frequency are beamed into the marble by a phased array transducer, with 64 sending and receiving piezoelectric ceramic elements. The beamed waves are reflected at the boundary to a different medium (e.g. air, iron, mortar) and detected by the same transducer (specifications for the UCS\textsubscript{1MHz} are given in table 2). For a pre-established ultrasonic velocity (m/s), the travel time (µs) is measured and the depth of the reflection calculated.

Table 2. Parameters for UCS\textsubscript{1MHz}.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MHz</td>
<td>Frequency</td>
</tr>
<tr>
<td>64</td>
<td>Number of elements</td>
</tr>
<tr>
<td>64 mm</td>
<td>Total length of the transducer</td>
</tr>
<tr>
<td>1 mm</td>
<td>Periodicity</td>
</tr>
<tr>
<td>0.1 mm</td>
<td>Gap between elements</td>
</tr>
<tr>
<td>10 mm</td>
<td>Total width of the transducer</td>
</tr>
<tr>
<td>4500 m/s</td>
<td>Average ultrasonic velocity</td>
</tr>
<tr>
<td>Rexolite\textregistered 1422, C-Lec Plastics Inc.</td>
<td>Matching layer, cross linked polystyrene microwave plastic</td>
</tr>
</tbody>
</table>

2.3. Coupling media

In order not to loose energy of the ultrasonic waves coupling media were used. The coupling in the UPV\textsubscript{46kHz} measurements was done with “Plastic-fermit”, a permanent elastic silicone polymer, and a polyethylene interlayer to protect the stone surface from contamination with traces of silicone oil. The measurements were calibrated with the coupling media in order to subtract the dead time in the both emitter and receiver before starting any measurements on the marble.

The coupling media which is normally used in sonography for medical investigation is not meeting the conservation requirements, it could leave stains or occlude the stone pores; therefore an alternative coupling method was chosen. First a layer for protection and to even out the rough surface of the marble of molten cyclododecane was applied. A second layer of a self-adhering film (a semi-conductor wave film SWT10+ by Nitto Denko) with a silicone surface was applied. In order to avoid air between the transducer and the coupling layers an acoustic gel (contact gel for diagnostic medical ultrasound by Sonogel) was used. The accuracy (+/- 0.45 cm) is influenced by the assumed wavelength, which has at 4.5 km/s and a frequency of 1 MHz a length of 0.45 cm.

3. Results and discussion

The average ultrasonic velocity of the marble column determined with UPV\textsubscript{46kHz} transmission measurements is 3.7 km/s. This value corresponds to a marble with increasing porosity, damage class 1 (s. table 3), and it was used as parameter for the UCT\textsubscript{46kHz} (s. Table 2).

Table 3. Classification of marble damage derived from velocity-porosity correlations after Köhler (1991), Galan et al. (1991) and Sizov et al. (1999).

<table>
<thead>
<tr>
<th>Ultrasonic pulse velocity $V_p$ [km/s]</th>
<th>Description</th>
<th>Damage class</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 5</td>
<td>Fresh</td>
<td>0</td>
</tr>
<tr>
<td>3 – 5</td>
<td>Increasing porosity</td>
<td>1</td>
</tr>
<tr>
<td>2 – 3</td>
<td>Progressive granular disintegration</td>
<td>2</td>
</tr>
<tr>
<td>1.5 – 2</td>
<td>Danger of breakdown</td>
<td>3</td>
</tr>
<tr>
<td>&lt; 1.5</td>
<td>Complete structural damage</td>
<td>4</td>
</tr>
</tbody>
</table>
In the UCT_{46kHz} map (fig. 3a) 2-3 layers (delimited with yellow circles in fig. 3b) are characterized by different UPV values, which correspond to materials with different physic-mechanical properties. In average the marble cylinder walls show a typical velocity of 4.4-4.6 km/s; the intermediate zone has slightly lower velocity of approx. 4.4 km/s and the inner core has 4.0 km/s to 3.8 km/s. The outer layer is estimated to have 6.5-12.5 cm depth; there is an intermediate zone with 4.5-6 cm thickness and the inner one 34 cm depth. The tomography shows furthermore that the drill core is not perfectly centered (s. fig. 3a and fig. 5).

Figure 3. The left picture shows a UCT_{46kHz} of the column with a slightly decentralized core. The right UCT_{46kHz} shows three layers with different UPV values. The diameter of the column is 64 cm; one unit bar is 10 cm.

The UCS_{1MHz} shows reflections at 8-10 cm depths (s. fig. 6a) and at 4-5 cm depth (s. fig. 6b). Following Müller (2004) a drill core taken on the backside of a column on the 1st floor of the market gate (seventh column from right) shows a thickness of the marble hull of 3.5 cm, while a different drill core taken from the eighth column from right on the 1st floor shows a thickness of the marble hull of 6 cm, but no lime mortar is present as the following layer. Based on Ruedrich et al. (2004) the composition of the marble columns of the Market Gate of Miletus is as follows (from outside to inside): marble with a thickness of around 3-5 cm, lime mortar (3.5-8.5 cm thick), brick tubes (4.5-6 cm thick) and the concrete mortar embedding the reinforcement with a diameter of around 34 cm. A schema of the column section is presented in the literature (s. fig. 4). The diameter of the inner core mentioned by Ruedrich et al. (2004) fits well with results obtained in this study with UCT_{46kHz}.

Figure 4. Assumed composition of the columns after Siegesmund and Ruedrich (2005): marble (white), lime mortar (yellow), brick tube (red), concrete (grey) and iron reinforcement (dark grey).

Figure 5. UCT_{46kHz} of the tested marble column with curved beams. The perimeter of the column is marked red. The diameter of the column is 64 cm; one unit bar is 10 cm.
Figure 6. The left sonogram shows a reflection at 6-7 cm depth. The sonogram on the right shows a reflection at 4.5 cm depth. The reflections are marked with a red circle.

4. Conclusions

UCT$_{46\text{kHz}}$ and UCS$_{1\text{MHz}}$ were applied on a marble column of the Market Gate of Miletus composed of several structural layers. With both investigation techniques the transition between two layers at 8-10 cm depth was confirmed. In the tomography map the transition of layers is recognized by a drop in the ultrasonic velocity, whereas in the sonogram by a reflection. Further layers could be only detected either by one or the other method: UCT$_{46\text{kHz}}$ detected a layer transition at 11-18.5 cm depth and UCS$_{1\text{MHz}}$ detected a reflection at 4.5 cm depth. On the one hand, low frequencies may be less able to resolve material changes in the surface zones than higher frequencies (Ahmad et al. 2009). The penetration depth of 46 kHz pulses is much higher, the attenuation considerably less in marble than 1 MHz, for this reason the deeper transition at 13-15 cm was not detected by sonography.

Both techniques together give complementary information. UCS$_{1\text{MHz}}$ is easier and faster to evaluate than UCT$_{46\text{kHz}}$ and has the advantage of a good detection of changes in lower depth near the surface, which may be relevant for the study of deterioration phenomena and consolidation interventions. The coupling media used in UCS$_{1\text{MHz}}$ was more time consuming than in UCT$_{46\text{kHz}}$ measurements, since the cyclododecane had to melt and be applied wet on the surface. Even though the cyclododecane is supposed to sublime without leaving residues, it may take several months to do so. The coupling media used in UCT$_{46\text{kHz}}$ did not leave any traces on the surface right after the measurement. Further research is needed for allowing the UCS equipment to detect reflections deeper than 12 cm.

Acknowledgements

The project for this study was funded by the Deutsche Bundesstiftung Umwelt. The authors would also like to thank both Wolfgang Maßmann, Head of conservation and Andreas Scholl, Director of Collection of Classical Antiquities for granting access to work on the Market Gate of Miletus. Peter Weber (Fraunhofer Institute for
Biomedical Engineering) is gratefully acknowledged for his help in the fieldwork as well as Steffen Tretbar (Fraunhofer Institute for Biomedical Engineering) for the support of the UCS and Rolf Krompholz (GEOTRON-ELEKTRONIK, Pirna) for lending a 350 kHz transducer for UCT.

References


Long-term Evaluation of the Conservation State of Marble Statues

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Abstract

Based on comparative investigations after a period of six years, a reduction of the ultrasonic velocity of 9% and 11% for two marble statues could be detected. The investigations on the objects were based on a newly implemented monitoring program using checklists and detailed mappings to document the development of the conservation state of the monumental statues in the historical center of Berlin, Germany. Traditional ultrasonic measurements were combined with surface hardness tests for selected representative areas using an equotip 3 device. In these areas, the water absorption was tested as well, using Karsten test pipes. In some areas and for different states of weathering, the results show a clear correlation between the surface hardness and the measured ultrasonic wavelength. The results of the water absorption tests underlined the differentiation of weathering forms. The investigations can help to characterize and distinguish between different forms of weathering, such as structural depth weathering or a softening close to the surface. By comparing the nondestructive and only minimal invasive test results with petro-physical compressive strength measurements of marble samples, a clear correlation between ultrasonic velocity, surface hardness, and capillary porosity could be identified. The results can help to calculate the stability assessment, plan the conservation, and make a prognosis of the ongoing weathering process. In conclusion, we elaborate a concept for conservation and restoration and make recommendations for a sustainable preservation of the sculptures.

Keywords: Ultrasonic velocity, Surface hardness, Weathering forms, Conservation

1. Introduction

For over 30 years, stone conservation has used ultrasonic measurements to evaluate the conservation state of marble. Today, making regular measurements can determine the state of conservation and the progression of the weathering process. A reduction of the ultrasonic velocity could be evaluated in most cases measured on marble statues in Munich and Potsdam (Köhler, Snethlage 2013; Pamplona, Simon 2012). Over a period of circa 20 years some of the most important marble statues in Berlin were investigated.

2. Objects of investigation

This study focuses on the marble statues of Generals Bülow and Scharnhorst, located in the historical center of Berlin, Germany. The Prussian generals Friedrich Wilhelm Bülow von Dennewitz (1755-1816) and Gerhard Johann David von Scharnhorst (1755-1813) played an important role in the German campaign of the Napoleonic Wars, 1813-1814 (in Germany also known as the European Wars of Liberation). Scharnhorst was also a key figure in the reform of the Prussian military. The sculptures are made from Carrara marble and are generally regarded as masterpieces of the important nineteenth-century “Berlin School” of sculpture. They were created by Christian Daniel Rauch (1777-1857), one of the most important sculptors of German classicism.

2.1. Rock material

Both sculptures are made out of nearly sculpture-quality white Carrara marble. Macroscopic observations show that the material of the Scharnhorst sculpture seems to have a finer crystalline structure than the Bülow
sculpture. The crystal size of the marble of the Scharnhorst sculpture is about 300μm, and the crystals are mostly polygonal and slightly curved in form. The material of the Bülow sculpture has a smaller crystal size of around 200μm. The crystal form again is polygonal but essentially straight.

2.2. History of conservation and restoration

The two sculptures have had a troubled history that has been documented in detail by the Berlin Federal State Office for the Protection of Monuments: In 1822 the sculptures were placed to the left and right of the “Neue Wache” (new guard house). The building on “Unter den Linden”, the main avenue in the historical center of the city, was formerly the main royal guard house and was built according to plans by Karl Friedrich Schinkel (1781-1841).

It is almost a miracle that the sculptures survived the Second World War, protected by a protective wall surrounding each monument. In 1950 the socialist government of the GDR had the monuments disassembled for political reasons, on the occasion of a meeting of its youth organization.

Both objects were stored on the nearby Museum Island. The Bülow sculpture was restored between 1954-58 for the first time, the Scharnhorst sculpture in 1960. In the case of the Scharnhorst sculpture, the eagle, the heraldic animal of Prussia was removed and the whole monument moved across the street from the historical location one year later. The Bülow sculpture remained in depot. In 1990 the Scharnhorst sculpture was brought to the state restoration workshop, restored and afterwards stored in another depot. Twelve years later both sculptures were placed back on “Unter den Linden”, this time not at their historical location but rather across the street, again for political reasons. Politics again was the reason why unknown perpetrators threw bags of paint on both sculptures during an anti-militarist demonstration in 2005. The sculptures were cleaned the same day on the request of the police, in accordance with a police directive to remove graffiti in the historical center within 24 hours. The cleaning was carried out using high pressure that caused damage to the surface. The next and last restoration of both sculptures was done one year later.

Figure 1. The “Neue Wache” building with the sculptures general Bülow (left) and Scharnhorst (right) around 1900.

2.3. Monitoring program and state of conservation

The Berlin Federal State Office for the Protection of Monuments saw itself moved to designate the long-term maintenance of the public bronze and marble statues in the centre of the city as a pilot project because of their outstanding artistic, historical and urbanistic value which has been implemented since 2009 and is the only such program of its size in Germany (Rieffel 2009). The program includes damage mappings, yearly inspections,
and collecting of all relevant data into checklists and reports.

Both sculptures show similar forms of weathering. These include the crumbling of crystals, disintegration, relief formation, and discoloration combined with microbial growth (Figure 2). The different forms of weathering were mapped during the first monitoring campaign in 2009 by restorer E. Böhme and a conservation action plan developed in 2013. Some of the damage to the surface can be traced back to the unsuitable cleaning campaign in 2005. In general the weathering of marble is caused by hygrothermal stress, solution decomposition, and frost bursting (Rüdrich 2003).

### 3. Measurement equipment and methods

For the ultrasonic measurements two different signal transmitters were used. The sculptures were investigated using a compressive wave transmitter with 250 kHz (area-shaped), the pedestals with 48 kHz (point-shaped). First the system USG 30 of the Geotron company was applied, and the objects measured by the method of longitudinal ultrasonic waves in direct transmission. The accuracy of measurements using this system is assumed to be 10%. During the measurements the transducers were coupled to the surface with suitable clay material. To evaluate the condition of the material the classification system formulated by Köhler 1991 was used (Table 1).

For surface hardness tests, an equotip 3 (proceq) portable testing device was used. The instrument offers extended capabilities such as measurements on almost all part geometries, with a high accuracy of ± 4 HL (0.5% at 800 HL) with automatic correction for impact direction. For each investigated area 10 individual measurements were done and the average value calculated. Capillary water uptake tests were done with Karsten test pipes and distilled water.

<table>
<thead>
<tr>
<th>class</th>
<th>wave velocity ( v_p ) (ms(^{-1}))</th>
<th>condition</th>
<th>porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>&gt; 5000</td>
<td>fresh</td>
<td>&lt; 0,5</td>
</tr>
<tr>
<td>II</td>
<td>3000 - 5000</td>
<td>increasingly porous</td>
<td>0,5 - 1,3</td>
</tr>
<tr>
<td>III</td>
<td>2000 - 3000</td>
<td>sanding</td>
<td>3,0 - 1,3</td>
</tr>
<tr>
<td>IV</td>
<td>1500 - 2000</td>
<td>fragile</td>
<td>3,0 - 5,0</td>
</tr>
<tr>
<td>V</td>
<td>&lt; 1500</td>
<td>disintegration</td>
<td>&gt; 5,0</td>
</tr>
</tbody>
</table>

### 3.2. Results of the measurements of the Bülow sculpture

The results of ultrasonic velocity measurements in 2006 showed values between 2.1 km/s and 4.1 km/s. The average value of all measurements is 3.40 km/s. In contrast to 2006, the measurements in 2013 showed values ranging between only 1.6 km/s and a maximum of 4 km/s. The average value reached 3.06 km/s, which amounts to a reduction of 11%. A clear reduction of the ultrasonic velocity could be detected for sections with a material diameter smaller than 20 cm (Figure 3). Most notable is the change of the ultrasonic velocity of the pommel of the sword. This pommel was replaced during the restoration in 2005. In 2006 a value of more than 5 km/s could be measured. Seven years later only 3.13 km/s was detected, which amounts to a reduction of around 40%.
The surface hardness ranges between 291 and 564 HLD. Most values of surface hardness of the tested areas (1, 3, 5, and 6) show a good correlation with ultrasonic velocity (Figure 4), and therefore indicate a penetrative loss of strength also related to surface weathering. The measurements of areas 2 and 4 with around 350 HLD show quite low values of surface hardness but an ample ultrasonic velocity of on average nearly 4 km/s and a classification of II following Köhler. This area of the original surface is well protected against direct wind and rain but the crystal structure is weathered (Figures 2[2, 4]) and 4).

Capillary water absorption, tested by Karsten test pipes only could be detected for area 1. This area has had the lowest HLD values (291) and as well the lowest ultrasonic velocity (1.6 km/s), which means it reached nearly the classification I (disintegration).

Figure 2. The surfaces of both marble statues show different conditions: 1) separation of crystals and formation of a relief, 2) weathered surface showing single crystals and a low relief formation, 3) moderate weathering, 4) moderate weathered area with microbial growth, 5) and 6) low weathered, nearly intact area with dirt deposits, 7) and 8) strongly back-weathered area with microbial growth, 9) moderately damaged surface, 10) separation of crystals by weathering and formation of a relief, 11) moderately weathered area, 12) nearly intact area, and 13) weathered surface.

Figure 3. The ultrasonic velocity related to the distance of measurement velocity

Figure 4. The surface hardness correlated with the ultrasonic
3.3. Results of measurements of the Scharnhorst sculpture

In a first campaign the sculptures were measured by ultrasonic velocity in 2006 after the last restoration. The sculpture show values between 2.5 km/s and 4.6 km/s and are reaching an average of 3.66 km/s. By the comparative measurements in 2013 values between 1.4 km/s and 4.4 km/s and an average value of 3.4 km/s could be detected. This comparative low weakening of the average value amounts to a reduction of 9%.

The highest values between 4.0 km/s and 4.6 km/s could be detected at compact areas such as the trunk of the sculpture. In 2006 as well in 2013 low ultrasonic velocity between 3.0 km/s and 4.4 km/s could be measured on free weathered arms and legs. Following the classification of Koehler, these areas are increasingly porous (II). The lowest values could be detected at filigree details such as fingers and robe folds. In 2006 these areas reached an average value of only 2.5 km/s. In 2013 an average value of only 1.7 km/s could be measured for these areas. The results show clear reduction of the ultrasonic velocity for sections with a material diameter smaller than 30cm (Figure 5). This may be due to a deeper penetrative weathering that developed in the case of the Scharnhorst sculpture, probably because the sculpture was exposed to weathering 27 years longer than the Bülow sculpture.

Surface hardness varies between 300 and 450 HLD. Nearly all values of surface hardness measurements show a good correlation with the ultrasonic velocity (Figure 6). This indicates a relation of the lost of structural and surface strength and supports the thesis of a penetrative structural weathering. Only the measurements of area 7 with around 450 HLD show high values of surface hardness but only a medium-sized ultrasonic average velocity of 3.1 km/s. This area of the original surface is water-proofed and still in good condition while the ultrasonic value indicates that a structural weathering has also affected the area.

Capillary water absorption, evaluated by Karsten test pipes could only be detected in area 1. This area has the lowest HLD values (300) and the lowest ultrasonic velocity (1.8 km/s), reaching the classification IV (fragile) following Koehler (Figure 6, Table 1).

4. Discussion

With the combination of the testing methods used different forms of weathering could be distinguished. If only low ultrasonic velocity and low surface hardness values are measured it can reasonably be concluded that the tested area is affected by a structural, penetrative depth weathering. This could be measured in case of the Bülow sculpture at area 1 and for the Scharnhorst sculpture at areas 1-4 (Figures 4 and 6). If water absorption also occurred in these areas, then the situation is in an acute critical condition. If the surface hardness values are high but ultrasonic values are only low, also depth weathering could be combined with the formation of a crust, for example due to dissolution of calcite and precipitation at the surface. If the surface hardness shows low values but the material a high ultrasonic velocity, the damage only is located at the surface. This is the case for example at the areas 2 and 4 of the Bülow Sculpture. This damage can be traced back to the unsuitable cleaning with a high-pressure cleaner in 2005.
For the investigated samples of Carrara marble in different conditions, in a comparison of samples from both sculptures a compressive strength of 40.89 N/mm² for weathered samples and of 105.52 N/mm² for non-weathered ones could be detected (Rüdrich et al. 2013). In the cited study the authors also presented a clear correlation between ultrasonic velocity and compressive strength. By fitting the measured values of the ultrasonic velocity into the diagram of Rüdrich et al. 2013, the average compressive strength of the Bülow sculpture can be determined to be around 95 N/mm² in 2006 and 90 N/mm² in 2013. The changes become clearer when looking at the results for filigree parts of the sculpture. For these areas a reduction by half up to a maximum of around 60 N/mm² and a minimum of around 30 N/mm² can be assumed (Figure 7[a]). For the Scharnhorst sculpture it looks quite similar: the average value reaches around 100 N/mm² in 2006 and 95 N/mm² in 2013 but the affected filigree details of the sculpture show a reduction even higher than the for the Bülow sculpture (Figure 7[b]). Possibly this can be traced back to its sustained period of outdoor exposure over a period of 27 years. The Scharnhorst sculpture was exposed to weathering for 117 years, the Bülow sculpture for 90 years.

The reduction of compressive strength and loss of material stability seems to be concentrated on the parts with a low material thickness and was presented already as a model as one result of a scientific project to evaluate the state of conservation of the marble statues on the castle bridge in Berlin (Figure 8; Rieffel 2010). The same weathering forms could be observed in the case of the Scharnhorst sculpture. Furthermore it becomes clear that even fresh material (like the pommel of the sword of the Bülow statue) shows a significant deterioration within the first years of outdoor exposition. Related observations were made in the case of the distortion of cladding panels from marble (Koch 2005). These panels show the biggest distortion within the first years followed by a continuous but weak deformation.

Only within the strongly weathered areas with an ultrasonic velocity of less than 2 km/s and a classification following Köhler of IV to V (Table 1) water was absorbed by capillary action. These areas show a low compressive strength between 20 N/mm² and 60 N/mm² connected to a surface hardness up to 300 HLD.

**Figure 7.** The results of the ultrasonic measurements inserted into the diagram of Rüdrich et al. 2013. The average values of the Bülow sculpture show lower ultrasonic velocity but a lower decrease of stability loss a) than the Scharnhorst-sculpture, b).

**Figure 8.** Model of the loss of stability dependent on the object geometry.

### 4.1. Conservation

The results of investigation have consequences for conservation, because only the strongly weathered areas can be treated by conventional methods. To ensure that a consolidation material is able to penetrate into areas with a damage class of III or II, vacuum impregnation methods have to be used.

One of these methods is the Acrylic Total Impregnation (ATI), developed by Wolf Ibach and successfully applied in many cases since the 1970s (Sobott, Ibach 2008). Monolithic marble sculptures were treated successfully, as could be proved by several ultrasonic velocity measurements after different periods of time (Pamplona, Simon 2012). The results presented in the latter article also show that after several years a
weakening of the ATI-treatment can be detected.

When using the ATI-procedure, one aspect that has to be kept in mind; marble has a relative high thermal dilatation of calcite, and the anisotropic behavior of the calcite-crystal is well known (Kleber 1959). The calcite-crystal shows an anisotropic thermal dilatation coefficient ($\alpha$) of $\alpha = 6 \times 10^{-6}$ in one and $\alpha = 26 \times 10^{-6}$ in the other direction. Thermal stress causes a physical loosening of crystal boundaries, deformation, and weathering (Siegessmund et al. 2000). Acrylic resins show a much higher thermal dilatation, ranging between 50 and 110 x 10$^{-6}$/K, around 5 times higher than calcite, which can lead to an increase of dilatation that bears the risk of causing damage. The highest effect on dilatation change at 60°C with an increase that reached between 0.4 to 0.6 mm/m around the double of an untreated sample (0.18 – 0.3 mm/m) could be observed in case of Carrara marble (Rüdrich 2003). Today, problems can be observed within the joints of the Beethoven-Haydn-Mozart-monument, located in Tiergarten/Berlin. The monument was made of marble and treated with ATI in 2007. Today nearly all joints are cracked or lost only 6 years after restoration. The biggest gaps can be observed in joints of the south-facing monument, leading to the assumption that the increase of thermal dilatation could be the reason. The biggest gaps can be found between old treated stone blocks and new untreated ones. Using the ATI-treatment for the two sculptures described in this paper could cause risks, because today many details were replaced by new marble during different campaigns of restoration. Today, both sculptures are no longer monolithic sculptures. To protect these important sculptures in the future, the possibility of producing new copies and placing the originals in a museum is being considered.

5. Conclusions

The investigations show that different parts of a sculpture weather in different forms and at different speeds. The combination of different investigations such as ultrasonic velocity, surface hardness, and water uptake tests can help to characterize and distinguish between different forms of weathering, such as structural, penetrative depth weathering or a softening close to the surface. By comparing the results of the nondestructive or only minimally invasive test methods with petro-physical compressive strength measurements of marble samples, a clear correlation between ultrasonic velocity, surface hardness, and capillary porosity could be identified. The results can help to calculate the stability assessment and make a prognosis of the ongoing weathering process. A highly detailed knowledge about the conservation state of an object makes it possible to develop the right conservation strategy.

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Research on Ultrasonic Detection Stone Sculptures of Qian Mausoleum - Tang dynasty

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Abstract

Qian mausoleum is the only tomb that a couple buried together, who both were emperors of Tang dynasty, the only empress in Chinese history, Wu Zetian and her husband Gaozong, Li Zhi. The mausoleum has a history of more than 1300 years. Around the mausoleum there are four gates, just traces of gates being left now, respectively eastern, southern, western and northern gates. On both side of roads outside four gates, totally more than 120 large-scale stone sculptures are distributed, which occupies an important position in the Chinese art history due to their art aesthetic characteristics. Of them, 108 sculptures are still standing on both side of the road outside the southern gate even now. They are all exposed in the open air. All the sculptures are of limestone. This paper takes the Wuzibei (Tablet without any words) for Wu Zetian with the regular shape of cube and a stone-man figure with irregular shape as examples in order to introduce the ultrasonic detection technology, the nondestructive method, to make an investigation inside the stone sculptures. The detections were done with the method of gridding for the tablets with regular shape, and the method of Ultrasonic CT(Computed Tomography) for that with irregular shape. The results of the detection give the positions and the trend of the cracks inside sculptures, which are the basis for evaluation of the conservation state and preventive preservation.

Keywords: Ultrasonic detection, Stone sculpture, Qian mausoleum

1. Introduction

This paper describes a method of nondestructive detection for the positions and the trend of the cracks and weathering band inside stone sculptures - Ultrasonic Detection, with a digital ultrasonic detecting instrument for nonmetal materials. By analysis of the velocity and amplitude of first received wave, we have detected the position of the cracks inside Wuzibei and Shushengjibei, which have regular shape of cube. By Ultrasonic CT method, we have analyzed the cracks and weathering band inside a stone lion and two stone men.

2. Theory and method of ultrasonic detection

2.1 Ultrasonic wave and natural stone

Ultrasonic wave is a kind of micro mechanical wave which can spread in solid, liquid and gas mediums. It may be differently attenuated when spreading in different mediums, and also it has different velocity in different mediums. The velocity and the attenuation are the two most important parameters for ultrasonic detection. For ultrasonic detection of stone, the available frequency is 20kHz-1000 kHz. The velocity and attenuation of ultrasonic wave in stone may be influenced by the density, water content, cracks and other factors of stone. It may be said that the amplitude and velocity of the first wave received are positive correlated to the mechanical strength of the stone, and the mechanical strength directly respond to the weathering condition of the stone.

Therefore ultrasonic detection is an appropriate method to detect, the position and trend of weathering band
and cracks inside stone.

For many reasons, there may be some cracks, crazings, splits on the surface and inside stone sculptures. Ultrasonic wave may directly go through the crack when the fracture surfaces combine closely, so the velocity must not be decreased but the amplitude may be attenuated seriously. For the situation that the fracture surfaces not combine closely, the wave may bypass the crack and the velocity may be decreased, and also to the amplitude. For the split that runs through the stone, the wave will not be received on the other side.

2.2. Application methods of ultrasonic detection on stone sculptures

2.2.1. Gridding method

Gridding method may usually be used for stones that have regular shapes. Testing points are arranged as grids. Amplitudes and velocities of ultrasonic wave between every point and the corresponding point on the surface opposite are collected to analyse the position and trend of cracks, and to evaluate the weathering condition of the sculpture.

2.2.2. Ultrasonic CT method

The principle of ultrasonic CT is showed in figure 1. Abundant data of wave time are collected by fanshaped testing. S1-Sn are the launching points, R11、R12…Rni、Rnj are the corresponding receiving points.

![Figure 1. Principle of ultrasonic CT.](image)

Hypothesize that there are N testing line in the section plane, and the section plane may be separated to M grids on request of calculating accuracy. The result will be got by solving the matrix equation below:

\[
\begin{bmatrix}
I_{11} & I_{12} & \cdots & I_{1M} \\
I_{21} & I_{22} & \cdots & I_{2M} \\
\vdots & \vdots & \ddots & \vdots \\
I_{N1} & I_{N2} & \cdots & I_{NM}
\end{bmatrix}
\begin{bmatrix}
S_1 \\
S_2 \\
\vdots \\
S_M
\end{bmatrix}
=
\begin{bmatrix}
t_1 \\
t_2 \\
\vdots \\
t_M
\end{bmatrix}
\]

\(l_i\) is the length of path \(i\) in unit \(j\);

\(S_i=1/V_j\) is the slowness of unit \(j\);

\(t_i\) is the wave time of path \(i\).

The velocity \(V_j\) of ultrasonic wave of each point in the section will be acquired by the reciprocal of each \(S_j\).
3. Detecting of sculptures of Qian Mausoleum

3.1. Wuzibei - gridding method

Wuzibei is the tablet for Wuzetian, the only empress in Chinese history. It is 6.30 meters high, 2.10 meters wide and 1.49 meters thick, the size of the base is 3.3×2.9×0.75m, and they have a weight about 100 tons in total.

By visual inspection, we found that there are four cracks on the tablet (figure 2):
1. A vertical crack goes east-west on the top part of the tablet, named crack 1; (figure 2-1)
2. An oblique crack exists on the southern-west part of the top, named crack 2; (figure 2-2)
3. Another oblique crack exists on the southern-west part of the underpart, named crack 3; (figure 2-3)
4. In the middle part of the tablet, there is a natural joint goes east-west across the tablet, the crack on the top might be developed from it, and in east part of the bottom is has also developed to a crack, named crack4. (figure 2-4)

![Figure 2. Visual inspection of cracks on Wuzibei.](image)

We detected the tablet with ultrasound by gridding method, taking amplitude and velocity information between the corresponding points east-west or north-south. Compared with the information of the corresponding perpendicular points, we got the trends of the cracks and weathering condition of the tablet. The spaces between the points are 20cm for the body of the tablet, the horizontal distances are 10cm and vertical distances are 20cm for the head.

The distribution figures and the velocities of each point are shown in figure 3(1-2), and amplitudes in figure 3(3-4).

![Figure 3. The distribution figures, velocities and amplitudes of each point of Wuzibei. 1. South-north points and velocities, 2. West-east points and velocities, 3. South-north points and amplitudes, 4. West-east points and amplitudes, Graphic symbol: velocity (km/s) ≥5.5, 5.0-5.5, 4.0-4.5, 3.5-4.0, 3.0-3.5, ≤3.0, amplitude (dB)(3) ≥55, 50-55, 45-50, 40-45, 35-40, 30-35, ≤30, amplitude (dB)(4) ≥45, 40-45, 37-40, 34-37, 31-34, 29-31, ≤29](image)

Compared with the visual inspection, by analysing the velocities and amplitudes of ultrasonic wave for each point, we got the conclusions shown below:
1. The velocities of all the points for South-north detection are greater than 4.5 km/s, shows that the density
feature of whole tablet is fine, and there is no honeycomb weathering occurred. The fracture surfaces of most cracks combine closely, so ultrasonic wave can go through.

2. For the vertical crack goes east-west on the top part of the tablet: the crack dose not influence the velocity too much, but the amplitude is decreased on the edge of the middle part of the head. So the edge of crack is there.

3. For the oblique crack on the southern-west part of the top: by the amplitudes, the crack goes obliquely from southern-east up to northern-west. It penetrates the tablet from west to east, but two-third from south to north. The velocity is not decreased seriously, means that the fracture surfaces of this crack combine closely.

4. For the oblique crack on the southern-west part of the underpart: the amplitude and velocity are both severely attenuated, means that this crack has gravely developed. The crack grows almost through the tablet, from 0.6m to 2.6-3.0m height with a depth about 0.5m.

5. For the crack in the east part of the bottom: the crack has a height about 1-1.2m, and a depth about. It influences the velocity not so seriously, but the amplitude severely. Means that the crack has been developed.

Figure 4 shows the diagrammatic drawing of each crack projecting on the south and east facades, and the three dimension diagrammatic drawing.

![Figure 4](image)

**Figure 4.** Diagrammatic drawing of each crack projecting on the south and east facades and three dimension diagrammatic drawing. 1. South facade, 2. East facade, 3-4. Three dimension diagrammatic drawing. Graphic symbol: Green: crack 1, Red: crack 2, Blue: crack 3, Yellow: crack 4.

### 3.2 Ultrasonic CT detection on West No.4 Stone Man

The West NO.4 Stone Man is standing beside the south road of the Mausoleum, it is 394cm high, 113cm wide and 80cm thick. It is covered with cracks, especially on the head and shoulders. The right leg is ruptured slantly (figure 5). We selected 8 sections as shown in figure 5 for ultrasonic CT detection. The underpart of right leg is separated from the body, and ultrasound wave cannot go through the boundary. So we did the detection for the two parts of section separately. For evaluating the weathering level of stone, we use a standard shown in table 1, which is normally used among the conservators. V0 is the ultrasonic velocity of fresh stone similar to the stone detected. For limestone V0 is about 6000km/s.

The ultrasonic CT graphs of each section are shown in figure 6. Conclusions from the CT graphs:

1. Section 1: the velocity of most part is between 1000-2000m/s, the lower part of the legs is decayed seriously.
Table 1. Standard to evaluate weathering level of stone.

<table>
<thead>
<tr>
<th>Weathering Level</th>
<th>( \frac{V_i}{V_0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Weathered</td>
<td>( \geq 0.9 )</td>
</tr>
<tr>
<td>Void ratio increased</td>
<td>0.75-0.9</td>
</tr>
<tr>
<td>Floor level of weathering</td>
<td>0.75</td>
</tr>
<tr>
<td>Slightly weathered</td>
<td>0.5-0.75</td>
</tr>
<tr>
<td>Moderately weathered</td>
<td>0.25-0.5</td>
</tr>
<tr>
<td>Severely weathered</td>
<td>( \leq 0.25 )</td>
</tr>
</tbody>
</table>

2. Section 2: the middle part of the legs moderately weathered, and there is a weathering band or crack going from the northern-east to the southern-west, the velocity of the weathering band is about 1500m/s.

3. Sections 3-4: the holistic strength of the middle part is good, the velocity is between 3000-6000m/s in most part, but there is weathering band or crack existing from the northern-east to the southern-west, for which the velocity is about 1500.

4. Section 5: the velocity of most part is about 1500m/s, means the part near the shoulders is severely weathered. The condition of the right shoulder is a bit better.

5. Sections 6-8: the head is seriously weathered, the velocity of most part is about 1500m/s.

For the weathering bands or cracks in the middle part of the stone man, we prefer to say that they are cracks.

4. Conclusion

4.1 Performance of detecting results and evaluation of ultrasonic CT

Wuzibei is a big tablet is 630cm high, 210cm wide and 149cm thick. It is about 100 tons in total. It has a regular shape of cube and has smooth surface for ultrasonic detect. That makes it possible to work with gridding method.
On Wuzibei, we have got 407 groups of ultrasound data, with velocity, amplitude and frequency spectrum. By these data we got the positions and trends of 4 cracks, and we had drawn three dimension diagrammatic drawing of them. The results of the ultrasonic test commendably meet the visual ones.

The stone man has an irregular shape, and it is difficult to make comprehensive detection on it. So we chose several sections that may tell the positions and trends of inner cracks to make ultrasonic CT detection. Fortunately, with the restoration works, we need to make holes to embed steel bolt to reinforce the same stone man, it made us possible to observe cracks by endoscope from the hole (figure 7). By the endoscope, we have seen several cracks in the middle part of the stone man, it agrees the result of ultrasonic test. Ultrasonic CT and endoscope have identical views, means that ultrasonic CT may give credible result.

4.2. Imperfection and uncertainties of ultrasonic CT

Ultrasonic wave is a kind of spherical wave when spreading in mediums, and it may spread in the tridimensional way. In ultrasonic CT, we just calculate the optimal path in a section by Optimum Route. That is the most severe imperfection of ultrasonic CT in principle. For solving this problem, it needs us to make tridimensional analysis of optimal path, and to develop a tridimensional method to detect the inner part condition of stone. That means onerous fieldwork and complicated calculation. For ultrasonic detection of stone, it may be restricted that defects smaller than the wavelength may not be found.

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Monitoring using Hyperspectral Imaging Analysis of Stone Cultural Heritage in Korea

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Abstract

In this study the monitoring on Maaeyeoraesamjonsang (Rock-carved Triad Buddha) at Yonghyeon-ri in Seosan, Korea was conducted taking advantage of hyperspectral image analysis. As a result of analysis, the damage rates at the time of dismantlement of protective facilities and for five years having elapsed after the conservative treatment were calculated to have brown discoloration 36.6%, white discoloration 3.3%, and biological damage 15.6%. The biodeterioration is a new damage type having not been identified at the time of conservation inside the protective facilities. The NDVI of creatures inhabiting on the surface of Rock-carved Triad Buddha is -0.19, which was analyzed to be lower than the vegetation inhabiting on the surrounding rocks, if it continues to be managed under a current environment the damage by creatures is judged to increase.

Keywords: Hyperspectral, Image analysis, Monitoring, Deterioration evaluation, NDVI

1. Introduction

As most of stone cultural properties are located in an outdoor they are damaged due to physical, chemical, and biological weathering. In order to conserve the stone cultural heritages on a long term basis the damage factors have to be able to be controlled in an optimized way by quantitatively understanding the damage condition and identifying damage factors. Recently as the non-destructive diagnostic techniques are developed a lot of damage evaluation method such as damage map preparation method, ultrasonic test, infrared thermography analysis were developed, and the studies for enhancing the reliability of measurement results continued to be in progress (Fitzner et al., 2004; Lee et al., 2010; Jo et al., 2012). In addition, the conservative treatment of stone cultural properties tends to be executed based on damage diagnostic results.

However at the current moment to assess the damage of all the stone cultural properties has many limitations. There are many stone cultural properties requiring the damage assessment, while in order to accurately diagnose a stone cultural property lots of budget and time are required. Due to this since the damage diagnosis and conservative treatment are conducted the continuous monitoring on the stone cultural properties is actually difficult. Accordingly for the long term conservative management of stone cultural properties the effective monitoring method is required.

In this study in order to monitor the changes in damage condition of stone cultural properties the hyperspectral image analysis technique was utilized. The hyperspectral image is an image with a very high spectral resolution composed with hundreds or more of consecutive bands, which is mainly utilized in the sector of remote sensing. In recent years, it is applied in various sectors of research such as water and crop management, vegetation distribution, and change detection. However, there are few examples utilized for the damage assessment of stone cultural properties and monitoring. Accordingly in this study the applicability as the stone cultural heritages monitoring technique by applying the hyperspectral image analysis technique to Maaeyeoraesamjonsang (rock-carved Triad Buddha) at Yonghyeon-ri, Seosan was discussed.
2. Current Status and Research Methods

2.1. Status of object

Maaeyeoraesamjonsang at Yonghyeon-ri, Seosan is the statue of Buddha with stylish sculptural form and unique composition to be evaluated as the best work of Baekje Dynasty, which was discovered in April, 1959 and designated as a national treasure No. 84 in December, 1962. Since then with a view to a long term conservation of rock-carved Triad Buddha the closed timber structure typed protective facilities was installed in July, 1965. However, as the public opinion is formed that due to protective facilities watching by tourists is limited, some of the wall of protective facilities was dismantled in March, 2006, and then the protective facilities were completely removed in December, 2007.

During the course of these changes in the preservation environment to determine the damage condition of Maaeyeoraesamjonsang various researches such as precise measurement, non-destructive damage assessment, slope stability evaluation, conservative environmental analysis were conducted. Research results show that due to temperature difference between the internal and external protective facilities the condensation has generated on the surface of rock-carved Triad Buddha, these moistures were shown to react with mortar applied for the structural reinforcement and for the salt weathering to generate. Based on this research result, to reduce the damage of statue in March, 2008 various conservative treatments such as surface contaminants removal, reinforcement, surrounding environmental arrangement were conducted. Like this many attempts for the conservation of Maaeyeoraesamjonsang at Yonghyeon-ri, Seosan were made through trial and error.

Figure 1. Conservation status of Maaeyeoraesamjonsang at Yonghyeon-ri, Seosan. (A) Appearance at the time of discovery in 1959, (B) Appearance conserved inside the protective facilities during 1965~2006, (C) Appearance of the wall of protective facilities having been dismantled in 2006, (D) Appearance of protective facilities having been dismantled in 2007, (E) Damage map prepared in 2008, (F~H) Photos before (F) and after (G) cleaning conducted in 2008 and mortar removal appearance (H).
2.2. Research methods

In order to monitor the changes in damage condition of Maaeyeoraesamjonsang at the time of dismantled protective facilities and in March, 2013, the time when five years had elapsed after the conservative treatment the hyperspectral image analysis was conducted. For the hyperspectral the spectral characteristic curve of the object at all the pixels constituting of the image with remote exploration method to continuously express the spectral characteristics of the object through approximately 200~500 spectral bands can be obtained. In this study by collecting the spectral information for 417,000 pixels for statue the image classification was conducted. The obtained range of spectral wavelength is between 250nm~1000nm, whose pixel were classified into 520 bands (Figure 2).

In order to understand the damage condition based on the obtained hyperspectral image the image classification was conducted. The image classification is the method to calculate the damaged area by grouping the spectrum by damage aspect, among the techniques under the use in a remote exploration the Spectral Angle Mapper method equivalent to the supervision classification was utilized. In addition, in order to determine the distribution and activity of creatures the NDVI (Normalized Difference Vegetation Index) was calculated. Such an image analysis was conducted taking advantage of ENVI program.

3. Research results

As the amount of spectral information obtained through hyperspectral photographing is vast, in order to quantitatively determine the damage aspects the image shall be classified through a statistical method. First, in order to identify the overall color information the RGB image was prepared by combining the bands of the red wavelength of 640nm, the green wavelength of 550nm, the blue wavelength of 460nm (Figure 3). Through this, it was identified that the brown discoloration, white discoloration, and green discoloration are occurring on the surface of Maaeyeoraesamjonsang.

In order to establish the baseline data by damage area the ROI (Region of Interest) was set and each spectral data was statistically analyzed. The distribution aspects of overall spectral information are shown to have the highest value at 500~600nm and the sharply decrease at 750~770nm. However, dependent on the damage aspects there are the differences shown in measurement values, and dependent on the wavelength the differences shown in patterns to be absorbed and reflected. In order to establish the library of differently occurring spectral patterns with each other the average, maximum, minimum, standard deviations by damage aspect were calculated. The statistical result of spectral data set by damage aspect is as shown in Figure 4.

As a result of image classification being conducted based on the above classification criteria and calculation of share ratio by damage area, the fresh area was calculated to be 43.9%, the brown discoloration area 36.6%,
the biological area 15.6%, the white discoloration area 3.3%, and the unanalyzed area 0.7%. The brown discoloration area was identified to have little difference from right after the conservative treatment was made in 2008, but on the right side of statue the white discoloration by salt recurred, while on the left side creatures were shown to be inhabiting.

**Figure 3.** Modeling result of band by wavelength (A; 640nm, B; 550nm, C; 460nm) and RGB color combination image.

**Figure 4.** Hyperspectral spectral statistical data by damage factors.
The brown and white discolorations are the damage aspects having been identified at the time of conservation inside the protective facilities, but creatures are the aspects newly appeared after the dismantled protective facilities. Accordingly in order to quantitatively the damage of creatures the NDVI was calculated. Typically, the green vegetation by chlorophyll shows slightly higher reflectance in a green wavelength region, little reflectance in a red wavelength region, and nearly 50% of high reflectance in the near-infrared region. On the other hand, the dead vegetation with chlorophyll not present shows higher reflectance in the visible region, but lower reflectance than a live healthy vegetation in the near-infrared region. The vegetation index can be calculated utilizing the spectral characteristics of these creatures, whose NDVI calculation expression is as follows.

\[
NDVI = \frac{\rho_{Near\ IR} - \rho_{Red}}{\rho_{Near\ IR} + \rho_{Red}}
\]

NDVI is calculated between -1 and 1, the more value of which becomes it means that the higher activity of vegetation it becomes. As a result of NDVI calculation, the biodeterioration area of Maaeyeoreasamjonsang shows the range of -0.25~0.13 and the average of -0.19, while the creatures inhabiting at the surrounding rocks show the range of 0.01~0.25 and the average of 0.13. Therefore, the activity of vegetation inhabiting on the surface of statue was shown to be lower than the vegetation inhabiting on the surrounding rocks. However if rock-carved Triad Buddha continues to be managed in such an environment as the present time the damage by creatures is judged to increase.

<table>
<thead>
<tr>
<th>Biological area of rock-carved Triad Buddha</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Stdev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maaeyeoraesamjonsang</td>
<td>-0.25</td>
<td>-0.13</td>
<td>-0.19</td>
<td>0.02</td>
</tr>
<tr>
<td>Biological area of surrounding rocks</td>
<td>0.01</td>
<td>0.25</td>
<td>0.13</td>
<td>0.04</td>
</tr>
</tbody>
</table>
4. Discussion and Conclusions

Maaeyeoraesamjonsang at Yonghyeon-ri, Seosan has been conserved inside the protective facilities for approximately 32 years from 1965 until 2007, since then which has been managed in the outdoor environment. According to the previous study results, the major damage aspects of rock-carved Triad Buddha at the time of protective facilities existing were identified to be white discoloration by salt crystal (gypsum), and brown discoloration by weathering of rock. Among these as the white discoloration was identified for the mortar applied on the upper rock bed to react with water, to flow down, and to occur, the surface washing was conducted together with removal of some mortar when conserved and treated in 2008.

As a result of monitoring on the changes in condition of Maaeyeoraesamjonsang at the time of dismantlement of protective facilities and for five years having elapsed after the conservative treatment taking advantage of hyperspectral image analysis, the white discoloration by salt crystal and the green discoloration by creatures were identified. In case of white discoloration, it was the phenomenon having occurred from before the dismantlement of protective facilities, due to the high possibility of reoccurrence it could be forecast, but the creatures are a new damage aspect not having been observed in the past. Accordingly for a long term conservation of rock-carved Triad Buddha the proliferation of creatures shall be interrupted through environmental control.

References

Non-destructive Detection and Mapping of Defect Zone of Stone Cultural Heritage Monument by Graduated Heating Thermography

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Abstract
Infrared thermography for stone cultural heritage monument mostly focused on the qualitative analysis to judge the location of defect zones up to present. This study carried out quantitative modeling for mapping of the blistering zone using the graduated heating thermography. To achieve these goals, the following steps were performed: acquisition of thermographic images by the passive and active methods, making the temperature distribution curve, establishment of the critical temperature and transitional zone, classifying the relative deterioration degree of the blistering zone, monochrome processing, vectorization, and deterioration evaluation. Analyzing the blistering deterioration degree of Magoksa Temple stone pagoda using the quantitative modeling, total area and average rate of blistering zones were calculated as about 2.6 m² and 7.4%, respectively. The modeling will improve the reliability of deterioration map through mapping for blistering zone since most deterioration map has overlooked to mark the blistering zones.

Keywords: Infrared thermography; Stone cultural heritage monument; Blistering, Quantitative modeling

1. Introduction
Most stone cultural heritage monuments have suffered complexly from various types of weathering and damage such as crack, blistering, scaling, bursting, disintegration, discoloration and biological colonization (Heinrichs and Fitzner, 2011; Jo et al., 2012; Lee et al., 2011; Stück et al., 2011). Among these deterioration categories, blistering is defined as creation of separated, air-filled and raised hemispherical elevations on the face of stone resulting from the detachment of an outer stone layer (ICOMOS-ISCS, 2008). This detachment is not easily detected with the naked eye because it usually occurs at the stone’s subsurface layers. Therefore, non-destructive detection and mapping of the blistering zone are very important for conservation of the original form of a stone cultural heritage monument.

One recently developed non-destructive method for blistering detection in stone cultural heritage monuments is infrared thermography analysis. This method is like a real-time imaging technique and creates a thermal map. In addition, it differentiates quantitatively between fresh and blistering zones from the surface temperature. However, infrared thermography for stone cultural heritage monuments mostly focused on the qualitative analysis to judge the location of defect zones up to present, so that it has difficulties mapping for the blistering zone and calculating its quantitative area (Jo and Lee, 2014b). Therefore, this study conducted infrared thermography analysis of the Magoksa Temples stone pagoda in Gongju and completed the blistering map through quantitative modeling and calculated the areas and percentage of blistering zones.

2. Occurrence and methodology
The object of this study is the five-story stone pagoda located in Magoksa Temple, Gongju (Figure 1a). The pagoda is composed of fine-grained quartz diorite, and its northern part was significantly damaged from a 1782 fire, and much of its original form was lost (Jo et al., 2012). The basement part of the stone pagoda has very
high occurrences frequencies of blistering and scaling (Figure 1b). Among these, the blistering was mainly derived from lithological defects and natural weathering not salts damage. In particular, the second body stone (west face) of the stone pagoda was in a comparatively good state in the 2007 investigation (Figure 1c). However, a blistering crack and small scaling were observed along the aureole of the embossed Buddha statue in a 2012 investigation (Figure 1d).

Infrared thermography analysis was performed using graduated heating thermography using an infrared heater with a halogen lamp (Philips, 15021Z), an active method (Kordatos et al., 2013). The thermography camera selected for temperature analysis was a TemrmaCAM SC660 (FLIR Systems, Sweden). In addition, the temperature characteristics were analyzed using the ThermaCAM Researcher 2.9 software (FLIR Systems, Sweden). The mapping of blistering zones was completed by AutoCAD (Autodesk, USA), Illustrator (Adobe Systems, USA) and vector transformation software.

### 3. Quantitative modeling for blistering zone

This study focused on non-destructive detection using infrared thermography, quantitative modeling for deterioration evaluation of the stone cultural heritage monuments (Figure 2). To achieve these objectives, visual examination and percussion method of the blistering zones were first performed. Thermographic images were then recorded at regular time intervals. In addition, the critical temperature and transitional zone of the blistering zone were then established by forming a temperature distribution curve. Lastly, the mapping of the blistering zone was completed by the monochrome process and extraction of vector lines (Jo and Lee, 2014b).

Analysis of the degree of blistering deterioration of the Magoksa Temple stone pagoda was conducted with the completed map; the total area and percentage of blistering zones were calculated as approximately 2.6 m$^2$ and 7.4%, respectively. Thus, there is a high probability of scaling on the area of the stone pagoda (2.6 m$^2$) if the conservation treatment is not applied to the blistering zones. Therefore, the blistering zones need conservation treatment such as joining and filling, and changes in the states of the blistering zones should be continuously monitored (Jo and Lee, 2014a).
4. Discussion and conclusion

This study was able to identify the location, area, and relative degree of blistering, and contributed to creation of scientific conservational systems by quantitative diagnosis of blistering zones. In addition, the possibilities of graduated heating thermography for blistering detection of stone cultural heritage monuments are approached. In the future, if quantitative modeling of blistering zones is actively applied to deterioration mapping, then the reliability of deterioration evaluation for stone cultural heritage monuments will be improved (Jo and Lee, 2014b).

However, comparatively blistering with thick surface stone layers (approximately 10 mm and above) and enclosed style blistering are difficult to detect using infrared thermography due to their low thermal signals, and their temperature appears to change after a long heating time. Accordingly, percussion method was also used to examine thick blistering layers and enclosed style blistering. Therefore, detection sensitivity according to the various blistering shapes should be analyzed from rock specimens in the future. Thus, infrared thermography has some improvements to the field of cultural heritage monument.

References

An Introduction on 3D Laser Scanning, Computer Simulation Technology on Chinese Pagoda Restoration after Earthquake

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Abstract

Cultural Heritage Conservation Center(CHCC) in Tsinghua University is a professional organization in the field of cultural heritage conservation in China. By relying on the extensive science and technology platform of Tsinghua University, CHCC always devotes to the new technology on the heritage conservation. On May 12th 2008, Wenchuan Earthquake caused considerable damage and destruction to the Pagoda of the Peacock Cavity in Sichuan Province. We decided to use the 3D Laser Scan technology from the beginning of the project. Thus, through the application of computer simulation technology, the rebuilding tower model enabled us to place accurate assessment on the destruction of the Pagoda and to find out the original location of each damaged component. The tower even can be rebuilt through the model in the computer which prevent disturbing the structure fragments. The technology of 3D Laser Scanning and computer simulation is successful in the preservation of stone. It is a direction for the scientific Heritage Conservation.

Keywords: Pagoda, Earthquake, 3D laser scan, Computer simulation

1. Introduction of CHCC

Cultural Heritage Conservation Center(CHCC) in Tsinghua University is a professional organization in the field of cultural heritage conservation in China. By relying on the extensive science and technology platform of Tsinghua University, CHCC always devotes to the new technology on the heritage conservation.

CHCC is dedicated to immovable heritage protection. These projects cover the world cultural heritage sites, national cultural heritage sites, including the kinds of ancient architectures, grottoes, archaeology sites, monuments, industrial heritage, cultural landscape, cultural routesand so on. The practices include master conservation plan, Survey, Documentation, Study on Restoration.

2. The feature of Chinese stone heritage

In China, Stone heritages include Grotto, Pagoda, Bridge and so on. Grottoes is one of the most important stone heritage. It is a kind of temples. People cut caves in mountain. There were many Buddhism sculptures and paintings in it. Grottoes have a long history in China. It began from 4–5 century with Buddhism coming to China along Silk Road from India. Our institute has many practices in grottoes from 2005. Now we finished about 20 grotto projects in 7 provinces.
3. Background of the pagoda

Anyue Grottoes are in Anyue County, Sichuan Province. Stone grotto generic class relics, of which there 8 national cultural relics. Anyue grottoes mostly caved during Tang and Song Dynasty. The peacock pagoda is 50 meters away peacock king grotto of Anyue Grottoes. It faces south. The plan of the pagoda is octagon, 10.55 meters high residue after the earthquake, divided into three floors. There are Sutra names on the surface of the side column of the pagoda. So it called Sutra name pagoda.

On May 12th 2008, Wenchuan Earthquake caused considerate damage and destruction to the Pagoda of the Peacock Cavity in Sichuan Province. Due to the unexpected destruction and the emergent rescue demand, this mapping and preservation project was completed in merely one month, within which the team had to cope with the complicated issues like rescue repairing and structural reinforcement.

Via the traditional handwork mapping method, there is little possibility to precisely describe the damage by the Earthquake and also hard to evaluate the current structural stability with accuracy. The mapping team decided to introduce the three Dimension LASER scan technology from the beginning of the project. In this restoration engineering design we try to use computer simulation technology.
4. Survey of damage

4.1. Earthquake damage

Peacock pagoda head directly affected by the earthquake destroyed the two orbs performance. Crashing members also smashed part of the tower eaves, beams and other underlying components.

4.2. Structural destruction

The whole pagoda is made of sandstone rocks. From the initial observation all the stigmas and eaves had no bite treatment. Between the enter column and the side columns of the first floor, there were still retained a layer of wooden beam to connect the stone columns. But most wood beams missed especially between the side columns. The missing beams caused the connection of the stone structure weakened and the integrity of the pagoda affected.

4.3. Weathering decay

The 3rd floor columns weathered severely damaged, partially eroded pillar nearly half of which two columns’ feet and stigmas cracked serious. Their supporting points located on the edge of cracking sites. If the decay continued, it could cause the columns lack of capacity. In the end the cornice stones without supporting would cause the top of the pagoda collapsed.
5. Scattered components analysis by hand and three-dimensional laser scanning

We use 3D Laser Scan to scan the pagoda as well as the stone pieces that drop by earthquake. There were more than 40 stone pieces drop. It was pit that after the earthquake local farmers collected all the stone piece in the temple. So we don’t know the pieces’ location after the earthquake. We tried to piece the pieces on the ground by hand and find their original location. And then, through the application of computer simulation technology, the rebuilding pagoda model enabled us to place accurate assessment on the destruction of the Pagoda and to find out the original location of each damaged component. In the end we find 9 components’ original location. They are on the top and the cornice of the pagoda.

6. Introduction of the restoration design

The pagoda restoration work included two parts: one part for the "5.12 Earthquake" falling component reset work, another part is reinforcement work for the pagoda itself. By the conservation process, it should be first reinforcement work, and then the falling components to be reset.

According to the survey, the damage was mainly on the 3rd floor of the pagoda. The project reinforced should be focused on the pagoda eaves column section on the 3rd floor. The restoration project need replace some individual columns and three floor beams and eaves. The components above 3rd floor should be dismissed firstly. After the reinforce project, then put back the components.

In the original construction system of the pagoda, the center column and eight side columns both bear the structure load. The center column supplied the most load, and the side columns supplied the eaves load. According survey, the side columns on the 3rd floor decayed very much, especially 2 of them. Yet all the stone columns had a long history above 800 years. Whether they decayed to lose all the strengthen, We could not replace a new one. For strengthen the structure integrity, we would supplement the wooden beams missed and
add 8 wooden columns behind the decay stone columns on the 3rd floor. Due to the structure calculation, the wooden columns could supply the eaves and roof load, if any side stone columns lose the supply.

According to the three-dimensional laser scanning simulation study of falling pieced components, it will clearly be able to find the original place and can completely reset. But not all the falling components could be found their original location. The museum would keep the components. Copy members should be selected with the same material as the original components. And the new components should be marked, for their authenticity.

7. Maintenance

The above program is for rescue by the pagoda renovation program after earthquake. In order to ensure long-term stability of the preservation of the pagoda, the program is also developed for the following maintenance and monitoring programs.
Regular cleaning and maintenance: Unplug the plants, cleaning moss, regular wood components, and stone elements surface corrosion, weathering treatment. Chemical protection experiment: select the same stone materials as the pagoda, do the chemical experiments for stone surface reinforcement, and test its strength and anti-aging ability. The experimental results will direct the chemical protection project in the future.

8. Summary

"5.12 Wenchuan Earthquake" is the most powerful earthquake after 20 century 50s. Many heritage sites in Sichuan and neighboring provinces affected. Although it did not damage much to Anyue Grottoes, the peacock pagoda experience the most damage after it built in Song Dynasty.

At the beginning of the survey and design work, we decided to apply the three-dimensional laser scanning technology. During the assessment and rehabilitation design process we used computer simulation technology. The introduction of new technology is the study tool and basis for the final restoration design.

It is very important the first time survey information after earthquake. It is pity that we did not survey at the first time. So it was hard to us to find the original location of the pagoda pieces, which during the rescue repair work is the most difficult part. Although we use the three-dimensional laser scanning and computer simulation technology.

As the three-dimensional laser scanning technology in heritage conservation project is still in the exploratory stage, there are many immature in practical work applications. The analysis found that the design process should be combined with the analysis on site and computer simulation of cracked components. Although the shape of three-dimensional simulation model of the component is very accurate, yet the scanning component texture and color information is still very limited. For example, the drop components’ surface contact with air for a long time part will weather and break. It is hard to judge the original location of the three-dimensional simulation model. Scanning and computer technology is just the tools and not instead of human judgment. It should be used as a tool to improve the accuracy and design work efficiency projects for conservation heritage.

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Modeling Impacts of Visitation on Cave Environments

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Abstract
Wall paintings of the Mogao Grottoes have survived for a millennium in the cool-dry cave environment in the northwestern desert of China. Visitor numbers have been steadily increasing, subjecting the wall paintings to greater stresses. The Grottoes’ wall paintings and conglomerate bedrock contains hygroscopic salts. The largest threat to the wall paintings is elevated humidity levels near or above their deliquescent humidity, 67% RH, of the salt. The carbon dioxide (CO₂) concentration, an indoor air quality (IAQ) parameter, was set not to exceed 1500 ppm in the caves for visitor comfort and safety. Two mathematical models, one for CO₂ concentration and the other for humidity, were developed for simulating the environment in caves. The models use known CO₂ and moisture emission rates for adults, measured air infiltration rates of the caves, and climate conditions of the caves and site. Predicted values and monitored data were compared over the 8-hour operational period as well as closed overnight. The CO₂ concentration coincided well indicating the validity of the model. However, the humidity prediction was nearly 200% above the monitored peak as well as equally faster decay rates, indicating lack of the buffering term, such as the adsorption/desorption of moisture by cave surfaces.

Keywords: Modeling, Cave environment, Preservation of wall paintings, Indoor air quality, Visitor carrying capacity

1. Introduction
The Mogao Grottoes (40° 2.236’N, 94° 48.230’E, Elevation: 1320 m) is located in the northwestern China, between Taklamakan Desert and Gobi Desert, along the ancient Silk Road. It contains 492 decorated Buddhist cave-temples, dating back between fourth and fourteenth century, carved into 1.6 km of a natural cliff face consists of conglomerate rock. Wall paintings and polychrome sculptures of the Mogao Grottoes have survived for a millennium in a cool-dry cave environment. The site opened to visitors in 1979, and the visitor number has been steadily increasing. As the site became an UNESCO World Heritage Site in 1987, the annual total of visitor to the Grottoes exceeded 500,000 in 2012. The majority of the visitors travel to the site during months of June, July, and August, the high tourist season, when the daily total can exceed 6000 visitors. Over 100 caves are available for various tours, however, some of the caves are visited by all visitors due to their popularity. With the recent economical prosperity in China, the political and economical pressure has been mounting to make the wall paintings available to ever growing cultural tourism of the Dunhuang region. However, the wall paintings will be subjected to greater stresses from the increasing visitation. And larger visitor numbers impact the quality of visit as the caves will be more crowded; viewing time for the wall paintings will be reduced; and air quality in the cave will be worsened.

The Mogao Grottoes’ conglomerate bedrock contains hygroscopic salts, mixtures of mainly sodium chloride and sodium sulfate, that deposited during its natural formation. Some of the salts have migrated to wall surfaces and into the wall paintings. The largest threat to the wall paintings with high concentrations of the salts is elevated humidity levels near or above their deliquescent humidity, 67% RH, which was determined by a series of laboratory measurements. This environmental condition causes the deliquesce of the salt mixture in the wall paintings and bedrock. This can result in de-lamination of paint layers and detachment of plasters and bedrock fragments. During the subsequent re-crystallization when the environmental condition return to dry, in-situ crystallization can result in disruption and flaking of paints and plasters. Therefore, for the protection of the
wall paintings, the highest allowable humidity was set to 62% RH, 5% RH below the deliquescence value for caves with high salt contents, in order to provide a margin of safety. (Maekawa 2013) Cycling of large humidity variations physically stresses wall paintings even if they do not contain the hygroscopic salts. This cyclic stress can result in the adhesion failure and mechanical failure of paint surfaces after years of the exposure.

Indoor air quality (IAQ) requirements have to be maintained in the caves for visitor comfort and safety as well as a good visiting experience. The carbon dioxide (CO$_2$) concentration, one of the major IAQ markers, in the ambient air is 350-450 parts per million (ppm). Higher than 3000 ppm has often been recorded in heavily visited caves, such as Caves 16, 328, and 148. Although widely varying recommended limits, 1000-3000 ppm, (ASHRAE 2011, Building Bulletin 101, DIN 1946-2) vary depending on the type of space and length of exposure as well as sources of the recommendation. The limit of 1500 ppm was selected for caves of the Mogao Grottoes, considering the short visiting time of 10 minutes in each cave and a museum-like viewing low-metabolic activity.

After establishing above limits for humidity and CO$_2$ concentration in the caves of the Mogao Grottoes, safe visitor numbers can be established for individual caves, if an accurate and reliable model can be developed to predict changes of the cave environment resulted from the interaction between the cave environment, visitor emitted bio-effluents, and the outside air. Therefore, an effort was undertaken to develop mathematical model to establish visitor carrying capacity of individual caves at the Mogao Grottoes.

2. Method

The environment in a visited cave is determined by the mixture of an undisturbed cave air, bio-effluents emitted by visitors, the outside air, the sorption or desorption by cave walls/floor, and the rate of infiltration of the outside air as shown in Figure 1. Although types and emission rates of the bio-effluents are known, the outside air changes with the weather condition. And rates of the air infiltration depends on architectural features of caves and the outside weather. The sorption or desorption rates of cave surfaces also change with the cave air. (Sissom and Pitts, 1972)

![Figure 1. Schematics of the moisture and CO$_2$ mass balance in a cave.](image)
As described earlier, levels of CO\textsubscript{2} and moisture are the major concern among the bio-effluents for preservation of wall paintings and IAQ. The other bio-effluents are not significant, if the CO\textsubscript{2} level is maintained below 1500 ppm. The thermal energy emitted by visitors is small in comparison to a massive thermal mass of the surrounding bedrock. Due to a constant atmospheric content of CO\textsubscript{2} as well as the negligible amount of sorption and desorption by cave surfaces, the above relationship simplifies. The moisture content of the outside air can change drastically in summer. The moisture sorption/desorption is assumed to be small compared to other terms in the equation when the entrance doors is left opened and the normal open-door infiltration rate is maintained.

Considering that the air inside the cave is well mixed, the moisture or CO\textsubscript{2} concentration, \(W\), in the cave air can be expressed by the following equation.

\[
\frac{dW}{dt} = \frac{S(t)}{\rho \cdot V} + \frac{Q}{V} \cdot (W_{\text{out}} - W(t)) \tag{1}
\]

where \(S(t)\) is the moisture or CO\textsubscript{2} emission rate by visitors, \(V\) is the cave volume, \(Q\) is the air infiltration rate of the outside air, \(W_{\text{out}}\) is the moisture or CO\textsubscript{2} content of the outside air. The above equation can be integrated over time to obtain transient or dynamic solutions. Individual terms of the equations are described in sections below.

2.1. Emissions by visitors

Human’s emission rates for CO\textsubscript{2} and moisture differ significantly depending on metabolic levels of the activity. The American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) lists the moisture and CO\textsubscript{2} emission rates for various activity levels for determining ventilation and dehumidification requirements for acceptable IAQ for comfort. Table 1 shows those emission rates for standing or slowly walking adults published by ASHRAE (2004).

Table 1. Representative rates for moisture and CO\textsubscript{2} productions by an adult in different levels of activity (after ASHRAE 2004).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Adult Emission Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moisture (gram/hour/ adult)</td>
</tr>
<tr>
<td>Standing</td>
<td>55</td>
</tr>
<tr>
<td>Walking</td>
<td>70</td>
</tr>
</tbody>
</table>

2.2. Air infiltration rate

Air infiltration rates are mainly driven by the temperature difference between the outside air and temperature of cave walls. In summer, the infiltrated warm outside air is cooled in the cave and falls toward the floor as the density increases. This movement induces a larger air circulation in the cave’s main chamber and, as a result, exfiltration of the cool cave air. Larger the temperature difference, higher the air infiltration/exfiltration rate. Therefore, the air infiltration rate changes over the day depending on the outside weather, and higher rates are recorded in the afternoon when the outside temperature is higher. In addition, wind pressures and turbulence levels of the outside air contribute to higher infiltration rates. The rates are also influenced by architectural configurations of caves. Obviously, the most influence comes from condition of the entrance, open-close condition of the entrance doors and doorways, as well as door type and fitting of the doors to cave openings if doors are closed. Blockage of the cave entrance by visitors also significantly reduce the air infiltration rate.

Due to the complexities involved in mathematically modeling the air infiltration rate for various architectural configurations of caves as well as weather conditions, the rates were determined through a series of field measurements under ranges weather conditions and caves. The tracer gas dilution method, using continuous gas sampling and analysis of the SF\textsubscript{6} gas as the tracer described by Lagus and Persily (1985), was
used in determining the rates of visited caves in summer months. And empirical relationships between the cave size and the measured rates were established. Open-door rates are expressed in the air change rate, volumetric flow rate normalized by the cave volume, and summarized in Table 2. Closed-door rates were between one and two orders of magnitude less than the open-door values.

Table 2. Ranges of normalized infiltration rates for caves of various volumes with entrance doors open.

<table>
<thead>
<tr>
<th>Cave approximate volume (m$^3$)</th>
<th>Range of infiltration rates (number of cave volume/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower limit</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>500</td>
<td>1.5</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
</tr>
</tbody>
</table>

2.3. Climate of the site and environment in Caves

The Mogao Grottoes site has a cold desert climate, cold-dry winters and hot-dry summers, with the annual average of 11°C and approximately 40 mm of annual rainfall with significant variations. Daily averages of temperature, humidity, and moisture content of air (humidity ratio) are 24-28°C, 10%-30% RH, and is 5-7 g of water/kg of dry air (g/kg), respectively, in June, July, and August. Diurnal temperature and humidity variations are 10-15°C and 10-30% RH, respectively, a typical for a desert climate. However, occasional high humidity and rain events, causes spikes of high humidity above 50% RH in summer months. These events increase the humidity ratio to 8-17 g/kg. The rain events are often preceded and followed by periods of high humidity conditions. Detailed climate of the site is described by Maekawa (2013).

Temperature in caves, 3-10°C in winter and 15-18°C in summer, follows the site climate with reduced short and long-term variations. The cave humidity, which averaged from approximately 10-20% RH in winter to 30-60% RH in summer, is highly influenced by the site’s weather conditions as well as by the visitation. Entrance doors of caves are normally closed shut, but, left open only when visitors are inside. Visitations into caves produce 1-2°C positive temperature spike as well as 5-10% RH positive or negative humidity spikes, depending on the outside humidity level.

3. Results

Comparisons of the predicted CO$_2$ concentration and humidity by the mathematical model and recorded CO$_2$ and humidity changes under a typical high-season visitation in a Cave 16 (1745 m$^3$) of the Mogao Grottoes on a hot-dry day in August 2007 is shown in Figures 2 and 3. The CO$_2$ and humidity sensors were positioned at the center of the main chamber. Numbers of visitors were manually recorded at the cave entrance as well as inside the cave. The entrance door of the cave was closed over night, from 4:30 pm to 8:30 am, and left open during visits. Multiple tour groups of 20-25 visitors, led by site guides, toured the cave for 5 to 15 minutes during the 8:30 am-4:30 pm operational hour. The air infiltration rate was set to 0.01 hour$^{-1}$ for the closed hours, from 4:40 pm to 8:30 am, 1 hour$^{-1}$ between 8:30 am and 12 pm, and 1.6 hour$^{-1}$ between 12 pm and 4:30 pm. And the ambient CO$_2$ level was 400 ppm.

The model generally predicted the CO$_2$ concentration changes well for the majority of the day. The rate of CO$_2$ concentration increase and its peak value, 1700 ppm, in the morning as well as the its decay over the sparsely visited lunch period were accurately predicted by the model. The rate of increase in the afternoon was over-predicted by 10-20%. It was likely caused by an increased air infiltration rate between 2:30 and 4 pm due to higher outside temperature and/or wind. Although the afternoon peak time was off-set by 30 minutes to one hour, the peak value, 1450 ppm, as well as the decay that followed were predicted well by the model. The model predicted CO$_2$ changes similarly well for other monitored periods of the cave as well as in other caves. These positive results provided a confidence for applying the model as a design tool for the IAQ management in caves.
Comparison of predicted humidity by the mathematical model and recorded humidity changes in the same cave and period as Figure 2 is shown in Figure 3. The same set of air infiltration rates used for the CO₂ prediction was used in the humidity prediction. And the humidity sensor monitored the condition was situated at the same location of the cave as the CO₂ sensor. The humidity ratio of the outside air was assumed to be constant at 6 g/kg over the day, however, the monitored data indicated that it varied between 0.5 and 1.0 g/kg over the day.

The model generally predicted the daily trend, increases and decreases, of humidity well. However, the model over-estimated the humidity increase by approximately 200% in the morning. The rate of humidity decay following the morning peak was also over-predicted by the model. Although the time for the afternoon peak was predicted well, the increase was again over-predicted by 200%. The predicted humidity decay after the visit had concluded was also slower than the recorded humidity decay. Similar discrepancies were experienced in other time periods in this cave as well as in other caves.
Considering the great success in predicting CO$_2$ changes in the same cave for the same period, these large discrepancies in humidity changes indicated that the absorption and desorption of moisture by the cave surfaces were significant in determining humidity changes in the cave environment.

4. Conclusions

Two mathematical models, one for the CO$_2$ concentration and the other for humidity, were developed to predict impacts of visitors on cave environments of the Mogao Grottoes for preservation of the wall paintings and IAQ. The models included the initial condition, visitor emission of CO$_2$ and moisture, and air infiltration of the outside air. They utilized published moisture and CO$_2$ emission rates of adult, range of measured infiltration rates of caves, and weather conditions at the site. Comparisons were made to evaluate the accuracy of the model using monitored environmental condition in one of frequently visited caves of the Grottoes during August 2007 in which humidity, CO$_2$, and number of visitors were recorded for every minute. The model predicted CO$_2$ changes in cave well; however, it over predicted humidity peaks by approximately 200%, although the daily humidity trend was predicted well.

Comparison of predicted and recorded results indicated that the sorption/desorption term was negligible for modeling the CO$_2$ concentration in caves, as expected. However, in modeling the moisture, the contribution of the sorption/desorption term was essential for the accuracy. This fact indicated that differences between the predicted humidity and measured values are likely to be the amount of moisture absorbed by hygroscopic materials in caves, such as walls, floor, and dusts. This also indicated that the placement of passive moisture buffer materials may be an effective method for controlling humidity in highly visited caves, even if the infiltration rates are moderate.

Acknowledgements

Contents of the paper were developed in a collaborative project between the Dunhuang Academy and The Getty Conservation Institute. The measurement of Mogao caves’ air change rates and recording of visitor numbers were jointly performed between Xue Ping, Zhang Guobin, Zhang Zhenmo, Hou Wenfang of the Dunhuang Academy and the author.

References

Conservation Environment of Korean Ancient Mural Tombs in the Period of the Three Kingdoms

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Abstract

In southern part of Korea peninsula, there are 5 ancient mural tombs of the period of the Three Kingdoms. Among these, Songsalli Ancient Tomb no. 6 in Kongju and Neungsalli Ancient Tomb no. 1 in Buyeo are the tombs of Baekje dynasty, Ancient Tombs with Wall Painting in Sunheung and Tomb of Eo Suk of Sunheung in Yeongju are the tombs of Silla dynasty, Ancient Tomb with Wall Painting in Goa-ri, Goryeong is the tomb of Gaya dynasty. These mural tombs have lots of historical values because of presence of ancient paintings. But nowadays, it is hard to see mural paintings within tombs that because damaged by physical, chemical, biological factors with specific environmental conditions. So, we have conducted temperature-humidity monitoring within 3 ancients mural tombs (Songsalli Ancient Tomb no. 6, Neungsalli Ancient Tomb no. 1, Ancient Tomb with Wall Painting in Goa-ri) for 1 year. And also, microorganism distribution within tombs investigated for integrated environment analysis. As a result, humidity always maintains 100% conditions because these tombs are restricted area in all of 3 mural tombs. Temperature changed at 2~4 months intervals with outdoor condition because burial mound (soil) functions like buffers. And it maintains low temperature for 10~20 °C which cannot grow microorganisms, but it need another conservation measure because we found psychrophilic fungi such as Geomycespannorum.

Keywords: Mural painting, Tomb, Microclimate, Biodegradation

1. Introduction

Ancient tombs are where the deceased is buried and show the symbol of death at the time. Tombs are directly influenced by natural environment but they are presented differently due to the recognition of death in the time’s society or cultural differences. Also tombs show the social status of the deceased and apply the society, the group’s religion, and belief of the deceased. Tombs can be constructed gigantic, may include various facilities in them, or fancy murals were painted in them (Jung, 2009).

Contents of murals in the ancient tombs in the ancient periods of the Three States in Korea generally showed customs, symbolic patterns, and four gods at the time. Customs are celebration of prosper life of the deceased. Symbolic patterns are mostly sun, moon, and stars representing the sky, or elements of the religion the deceased believed in. Four gods are painted in the order of direction god; blue dragon on left/East, white tiger on right/West, phoenix on front/south, and Hyunmu on back/north (Han, 2009).

These murals in ancient tombs were mainly constructed in Koguryo among the Three States, and very few in Baekjae and Shilla. There are 5 mural tombs in the South from the Three States. Among them, Tombs of Baekjae are Songsalli Ancient Tomb no. 6 and Neungsalli Ancient Tomb no. 1, and Shilla tombs are Ancient Tombs with Wall Painting in Sunheung and Tomb of Eo Suk of Sunheung in Yeongju, and for Gaya, there is Ancient Tomb with Wall Painting in Goa-ri. Mural tombs are historically very important as they consist of paintings.
Ancient tombs are separated from the outside, and maintain low temperature and high humanity similar to burial environment. If outer air enters due to excavation, natural environmental condition in the tomb changes and causes condensation from temperature difference, or microorganism development came from the outside (Chung, 2007). This continues to serious damage on murals inside by physical, chemical, and biological factors and the original forms are hard to recognize.

Therefore, causes of damages on murals in ancient tombs in Korea are analyzed, and to establish preservation plans, inside and outside environment monitoring for Songsalli Ancient Tomb no. 6, Neungsalli Ancient Tomb no. 1, and the Ancient Tomb with Wall Painting in Goa-ri are executed. Also, distribution of microorganisms in the inside was examined to establish comprehensive preservation environment plans (Chung et al. 2010; Chung et al. 2012; Han et al. 2013; Chung et al. 2013).

Figure 1. Views of ancient tombs and murals inside. (Left; Songsalli Ancient Tomb no. 6, middle; Neungsalli Ancient Tomb no. 1, right; Ancient Tomb with Wall Painting in Goa-ri)

2. Material and methods

Inside and outside environment monitoring checked the changes of temperature and humidity in the tombs with the temperature and humidity sensor (HMP155, Vaisala, Finland) by space. In burial room, the surface temperature sensor (DTS12G, Vaisala, Finland) was installed to interpret inside condensation conditions. To check influences of the outside to the inside tombs, the multi temperature and humidity sensor (WXT520, Vaisala, Finland) was installed. Measuring range of the temperature and humidity sensor (HMP155) is -80~60°C (temperature), 0~100% (humidity), accuracy is ±0.05~0.2°C(temperature), ±0.6~1%(humidity). Measuring range of surface temperature sensor (DTS12G) is -80~60°C, accuracy is ±0.08°C at 0°C, type is resistance, Pt-100. The real-time data were automatically wirelessly saved in the computer near every 10 minutes. Saved data are downloaded by the real-time remote program for environment analysis.

To analyze the correlation and degree of danger between the environment of ancient tombs and microorganisms, microorganisms in the air of outside and inside tombs are collected. An air collector (APB-708000, BUCK, USA) was used by space unit to collect each twice by passing 100L of air to the PDA(Potato Dextrose Agar). Collected microorganisms were incubated in a 28°C for 3~4 days. Sterilized smear bars collected microorganisms on walls. Collected microorganisms were smeared on a PDA and incubated as above. Microorganisms among grown ones that are visible with naked eyes are pure-separated. Pure-cultured fungi inoculated on a PDA and germs on a NA then incubated in a 28°C medium for 3~4 days. Incubated microorganisms were classified in level one for group form, color, and size. For the species identification, 18S rDNA region was analyzed by sequencing.
3. Results and discussion

3.1. The inside and outside temperature and humidity

In case of Songsalli Ancient Tomb no. 6, monthly outside and inside temperature comparison confirmed that the inside temperature changes in about two months compared to the outside temperature. Throughout the year, the highest open air temperature was 26.1°C in July, while the highest temperature in the tomb was 20.4°C in October. The tomb’s summer is October, and this is the most cautious time for microorganism.

Figure 3. Monthly outside and inside temperature comparison. (Upper: Songsalli Ancient Tomb no. 6, bottom: Neungsalli Ancient Tomb no. 1)
The Monthly outside and inside temperature comparison of Ancient Tomb with Wall Painting in Goa-ri confirmed that the temperature changes in 1~2 months. The outside temperature was highest in August as of 26.8℃, and the inside temperature of 22.1℃ was the highest in September. Both tombs have summer in September.

The Monthly outside and inside temperature comparison of Neungsalli Ancient Tomb no. 1 confirmed that the temperature changes in 4~5 months. The outside open air was highest in August as 27.8℃, but the inside tomb had highest temperature of 19.2℃ in November. Summer of the inside tomb comes in November, and there is a difference between Songsalli Ancient Tomb no. 6 and Ancient Tomb with Wall Painting in Goa-ri.

The relative humidity in all three tombs was not related to the amount of humidity in the open air because the structures of tombs are almost 100% sealed throughout the year.

### 3.2. Condensation on walls in ancient tombs

The condensation in the inside tombs does not occur throughout the year, but the location shifts in order to changes in the inside temperature and surface temperature. In Songsalli Ancient Tomb no. 6, relatively lower temperature of the ceiling to that of the floor in winter causes condensation on the ceiling and then the location shifts to the floor in summer.

The location shift of condensation according to season in Ancient Tomb with Wall Painting in Goa-ri was similar to that of Songsalli Ancient Tomb no. 6. From winter to late spring, there was condensation on the ceiling, then from summer to fall, the location shifted to the floor. Both tombs were checked with the condensation prediction and actual quarter research through the relationship between space temperature and surface temperature. However, Ancient Tomb with Wall Painting in Goa-ri shows condensation on the ceiling throughout the year.

The lower annual surface temperature on the ceiling and floor of Neungsalli Ancient Tomb no. 1 compared to the air temperature would cause condensation in all spaces.

![Figure 4. Condensation in the ancient tombs.](Left: Songsalli Ancient Tomb no. 6, middle: Neungsalli Ancient Tomb no. 1, right: Ancient Tomb with Wall Painting in Goa-ri)

### 3.3. Distribution of microorganisms inside the ancient tombs

The result of microorganism distribution in the ancient tombs shows the number inside was less than outside. Collected and identified fungi confirmed *Aspergillus* sp., *Penicillium* sp. as dominant species, and these are generally known floating bacteria in air. Also *Bacillus* sp. was confirmed as dominant species.

Microorganisms that are confirmed in more than 2 tombs are 5 fungi and 5 bacteria. Among them, *Bacillus cereus*, *Bacillus megaterium*, and *Bacillus* sp. appeared in all 3 tombs.

The comparison between the temperature inside of the tombs and growth and development conditions of microorganisms from separation identification and microorganism outbreak prediction led to the action plans.
Table 1. Distribution of microorganisms inside the ancient tombs.

<table>
<thead>
<tr>
<th>Species</th>
<th>Songsalli Ancient Tomb no. 6</th>
<th>Neungsalli Ancient Tomb no. 1</th>
<th>Ancient Tomb with Wall Painting in Goa-ri</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fungi</strong></td>
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<tr>
<td>Aspergillus sp.</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Aspergillus versicolor</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Cladosporium cladosporioides</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Penicillium copticola</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Purpureocillium lilacinum</td>
<td>O</td>
<td>O</td>
<td>O</td>
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<tr>
<td>Bacillus cereus</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Bacillus megaterium</td>
<td>O</td>
<td>O</td>
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<tr>
<td><strong>Bacteria</strong></td>
<td></td>
<td></td>
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<tr>
<td>Bacillus sp.</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Bacillus thuringiensis</td>
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<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Paenibacillus terrae</td>
<td>O</td>
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<td>O</td>
</tr>
</tbody>
</table>

4. Concluding comments

This study monitored temperature and humidity preservation environment of three mural tombs from the Three State Era and analyzed the comparison. The environment monitoring confirmed that the ancient tombs show specific environment from others with the representative state of temperature change in certain time difference from outside environment. This phenomenon showed difference between three tombs from location, geological features, and artificial burial mound. The relative humidity inside with murals was 100% maintained as they are all sealed.

Among air in the space, the condensation occurrence time was predicted with air temperature and surface temperature, and this also checked the shift of moisture. In case of Ancient Tomb with Wall Painting in Goa-ri, the condensation on the ceiling from winter to spring may cause mural damage, and Neungsalli Ancient Tomb no. 1 also may have damage on murals due to condensation.

Figure 5. Prediction of microbial growth depending on internal temperature (Goa-ri Ancient tomb).

The distribution of microorganisms in ancient tombs confirmed fungi and bacteria in all three tombs as floating bacterial and soil microbe as dominant species. Also, the inside tombs have relatively less number of microorganisms compared to general space, but its unique feature as highly humid environment causes very high risk. Microorganism outbreak prediction according to the growth and development condition of
microorganisms was established and three tombs are safe or alerted except from September to October, the hottest time of the year. However, *Geomycespannorum* collected in Songsalli Ancient Tomb no. 6 is cold-resistant that demands constant monitoring.

With this study, three mural tombs need more stable environment to preserve murals. Condensation occurs due to temperature difference inside, that may cause damage on murals therefore surface condensation control system must be established in the future. Also, air temperature control system for microorganism control is necessary as well. The surface condensation control system and air temperature control should be operated under selective environment preservation management, not throughout the year.

References


A Study on the Conservation Trends of Buddhist Mural Paintings in Korea

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Abstract

Over the last century, the conservation effort was continuously done on temple wall paintings in Korea, those that are made of soil. Based on the result of researches on conservation related studies conducted from 1980 to present, at first it focused on practical conservation treatment. Then since 2000, conservation is carried out based on the results from scientific researches. There have been a number of efforts to prepare conservation measures more appropriate and stable to wall painting properties. Therefore, with the help of researches, more applications methods are found in particular about the effectiveness of color-layer solidifying agents and wall structure reinforcement.

Keywords: Mural paintings of Buddhist temples, Conservation, Soil, Synthetic resin, Glue, Seaweed

1. Research background

In Korea, it was only recent when the significance of wall painting conservation was understood. Therefore, there were a number of trials and errors because focus was placed on practical works that repairs damaged cultural assets, without having systematic consensus/discussion and establishing our philosophy of conservation. Most of wall paintings found in Korea are temple wall painting (made of soil). Therefore, once it is damaged, it is difficult to restore. For the same reason, a number of works are still exposed without repair, and some of them are permanently lost while repairing buildings (Han, 2003).

The history of conservation for temple wall painting started from the conservation of wall painting of Josa Hall in Buseok temple in Youngju in 1916. So far for about a century, there has been a gradual improvement. However, the conservation effort in the beginning merely applied the method and materials used in Europe, while there was few researches done on the application of conservation material in consideration of wall painting properties (which were made of soil). These still show instable results even until now. In particular, those acryl solidifying agent and lime mortar (that were used in 1980~1990) caused various side effects. Since 2000, it focuses on the development of wall painting conservation based on advanced technology and more scientific studies, reflecting trials and errors from the past. Reinforcement concept of conservation treatment is applied to those wall paintings that had been repaired or treated for conservation in the past.

Therefore, this study investigates previous researches in different times and the issues of early conservation treatment methods, followed by an introduction of proactive development process and the trend of soil wall painting conservation treatment. At the end, its significant will be reviewed for looking for suggestions.

2. Researches on the conservation of soil wall paintings

The researches on the conservation of wall painting started from the early 1980’s. Since 2000, there were more active researches done. There is few records on wall painting conservation after 1945. However, some could be found from building repair reports. This study investigated and summarized the study on conservation for temple wall paintings in Korea from 1980’s to 2012 (Lee, 2013).

There found a total of 71 studies for the conservation of temple wall paintings in Korea from 1980’s to 2012
Among these, those studies about conservation theories on temple wall paintings were 12 cases. 22 cases were about scientific studies such as optical investigation, and non-destructive analysis. Also, there are 11 studies on the conservation treatment process of damaged wall paintings, and 17 studies on the investigation of wall painting conservation condition. There found 9 cases of comprehensive studies that encompass the condition/conservation condition of wall painting, material analysis, safety review and systematic conservation treatment. Based on the study statistics, study frequency shows that there were more researches done since 2000. Frequency shows the most for analysis and investigations. Also, many conservation studies and status reports were produced.

There were almost few studies done on the conservation research on temple wall painting until the early 2000. However, since 2000, there were a number of active researches done. This trend can be deemed that more conservation treatment was widely used along with gradual increase in conservation studies since 1990’s. Up until the early 1990’s, there were few researches done. It shows a slight increase in the number of researches until the early 2000. However, there was no significant change. It was the time when conservation treatment on wall painting started, where most of works focused on practical conservation treatment and analysis. Therefore, there were only a few scientific researches for conservation treatment. It seems to be the time of transition period that proposes the necessity of researches while conducting conservation treatment.

After the year 2000, the scope of research widened to various topics about wall painting conservation. More practical researches were conducted that can be applied to conservation treatment along with theoretical studies, including damage factors and conservation measures. Also, there were more research results that were far more significant than previous studies, such as reinforcing material for pre-treatment in the past, and wall painting safety analysis.

3. Trends of conservation treatment on soil wall paintings

3.1. Transfer of the first large-sized soil wall painting in Korea: Wall painting behind the Buddha’s statue of the main hall in Bongjeong temple (1999)
On January 16th, 1997, a wall painting behind the Buddha’s statue was found while repairing paintings behind the Buddha's statue of the main hall. This wall painting shows a similar style of the early Sutra of the Lotus illustration of the early 15th century. Therefore, it is estimated to be from the year of 1435. It is an important painting to the study of the Vulture Peak Assembly in the late Chosun Dynasty (Park, 2000).

In 1997, the condition of wall painting was severely damaged such that the wall structure was damaged into three parts due to distortion, which has a significant impact on structure. Also, there found detachment and exfoliation on colored layer due to impurities and fungus. In 2000, the comprehensive disassembly and conservation treatment was carried out for the wall painting behind the Buddha’s statue. Along with infrared irradiation and pigment analysis, some part of wall was removed and its weight was reduced by applying stucco style disassembly and reinforcement method for about 3 years period.

In order to restore smoothness of distorted wall and also to reduce the weight of wall painting, parts of the first plastering and double wall layer were removed such that the thickness would become 40mm. The removed surface was reinforced by using soil. Light-weight aluminum structure was attached onto the back of wall, and a wooden frame was installed. Along with the restoration on cracks and loss on wall surface, there were cleaning works of solidified impurities and solidifying treatment (PV Ac, 1~3%) on colored layer. After completing the conservation treatment on wall painting, it was designated as a national treasure no. 1614 on April 22nd 2009, and is being stored in the storage of temple.

3.2. Restoration to the original condition of wall painting: Wall paintings on the inside slope wall of Geukrak Hall in Muwhi temple (2005)

There are 30 pieces of wall paintings on the slope wall of Geukrak Hall in Muwi Temple in Gangjin. They are currently kept in a museum. It was originally decorated in inside of Geukrak Hall. The preaching on the east wall and Amtabha on the west wall was painted at the same time when the wall paintings behind Buddha’s statue were painted. They used the styles of Goryeo Buddhist Paintings (Park, 1999). The rest of wall paintings were repainted on the fishing layer or newly painted in the late Chosun Dynasty. The wall paintings were disassembled since 1956. Then the disassembly and conservation treatment were carried out until 1979. In 1984, some reinforcement on color layers was carried out.

Until 1984, the damage on wall was reinforced with plaster mortar, and then the wall painting was stored in a protection frame made of plywood. For the solidifying colored layer, acryl and synthetic resin (isocyanate) were used. It showed that these repair materials are detached, peeled off and exfoliated from wall paintings as the time went on (Konkuk Univ. Fine Art Conservation Inst., 2006).

In 2005, the conservation treatment was carried out to supplement the pre-treated section. Repair parts that caused damages to the wall were selected and removed. Then they were reinforced with soils. Colored layer was solidified with low-density vinyl acetate (PVAc, 1~3%), in consideration of modified properties due to synthetic resin. The wall structure was reinforced by using Aluminum honeycomb. The conservation treatment in 2005 minimized the removal of wall structure, by applying a light-weighted support. This resulted to structural stability by preserving the original form of wall structure.

3.3. Conservation Treatment on large-sized paste-on wall paintings: Background wall painting behind Buddha’s statue in Heungguk temple (2008)

Suwol Buddhist Goddess of Mercy in Heungguk Temple in Yeosu is a large paste-on wall painting that is rare in wall paintings in the East. This wall painting is estimated to be painted in 17th century, which has a similar style with the painting behind the Buddha’s statue. Its wall was made of soils, and finished with mulberry textile paper on the wall, where the painting was done.

In 2008, there was the first conservation treatment on paste-on wall painting in Korea. The wall painting had a vertical crack on wall painting along a small reinforcing post inside the wall. Also there were exfoliation between finishing layer and paper, and damage to colored layer. The analysis and investigation were carried out on the manufacturing method and structure of wall painting, and their properties. As a result of FT-IR analysis,
some found that there is organic material of glue-type that might have been used in colored layer (Hanrim Conservation Tech, 2008).

After opening papers on damaged section of wall painting, wall structure was reinforced with soil and glue. Then reinforcement was carried out on damaged tributary and colored layers. Damaged tributary layers were attached by using plaster glue and Dak paper. Soil structure was reinforced with soil and glue. Then damaged colored layer was solidified with low-density plaster glue. By classifying tributary and wall experts, the conservation treatment was carefully conducted, which made possible to prevent damages for different material on wall painting.


The white-clothed Buddhist Goddess of Mercy of Bogwangmyeong Hall in Whibong Temple in Wanju shows the style of Buddhist painting of the late 17th century. It is one of the few large-sized wall paintings behind the Buddha statues in Korea. In 2010, the wall was treated with the stabilization on color layers (which had been powdered) and the wall reinforcement (that was structurally unstable). In order to find structural stability on wall paintings behind Buddha statue, ultrasonic analysis and radiation irradiation were carried out. The result of these safety analysis depend on conservation treatment and monitoring after obtaining efficient information, including the condition of inside of wall paintings and the wall painting surface properties (Baekje Cultural Heritage Conservation Inst., 2010).

The structural safety of wall was found to be weak. Therefore, after opening the front section of wall behind Buddha’s statue, it was found that there was an extensive damage and cracks that propagates through the front section of wall. It was reinforced by mixing film of paint glue and soils on the damages and cracks. The colored layer was relatively stable. Therefore, low-density (1%) of glue was used to solidify on sections that are being powdered.

3.5. Re-treatment on conservation treatment in the past: Exterior Wall Painting of Maitreya Hall of Geumsan temple (2013)

The total number of wall paintings is 187 pieces on the exterior wall of Maitreya Hall in Geumsan temple. It is believed that they are repainted a number of times after the building went through repair and improvement. The wall paintings follow the traditional structure and style of temple wall paintings in Chosun Era, which are made of soil. However, there was a change of wall painting structure after conservation treatment particularly since 1992.

The wall paintings on 2nd and 3rd floor were disassembled and treated by using stacco a masllo and strappo methods from 1992 to 1993. The color layers were hardened by using Paraloid B-72 (1~10%) (Art History Association of Korea, 1993). Since then, while wall paintings were exposed to outdoors, damages started to become extensive. For instance, their wall surface and structure reinforcement layer were separated, or color layers and finishing layers were either deformed or detached.

Currently, the wall paintings of Maitreya Hall are undergoing stabilization and structure reinforcement on the damages. For conservation treatment, it includes the analysis of wall properties, various investigations on damage condition and causes, and the restoration works on damaged section. The reinforcement works on wall painting surface is carried out by: 1) analysis of settling condition with synthetic resin material (Paraloid B-72), which is followed by softening solids with thermal infrared ray.

After reinforcement in the past, the reinforcement works on wall painting removed the structural layer with damages. Then additional reinforcement is being carried out by applying a light structure and soil reinforcement onto the wall structure (Lee et al., 2011).

4. Review

Based on the previous conservation studies done on wall paintings after 1980’s, they focused on conservation treatment. However, since the year of 2000, a conservation method was prepared based on the analysis of wall painting conditions and materials, instead of considering only conservation treatment. So, the
trend is to establish a systematic conservation treatment based on the analysis result. Also, there is a significant improvement in record management, which lead to comprehensive research results.

For instance, for the conservation treatment of wall paintings behind Buddha statue in Bongjeong Temple in Andong, the weight of wall paintings were decreased while maintaining the same thickness, which resulted to the increase in structural stability. Also, the use of acrylic resin was rejected, and soluble vinyl acetate resin was applied in low density. The wall painting on the slope of inside wall in Geukrak-jeon of Muwhi temple was restored to the original condition from repair damages. However, there is still an issue of removing both reinforcing repair material and synthetic resin (that forms a film of paint applied to color layers in the past). For the wall paintings of Heungguk temple, it was possible to settle permanently by using glue on reinforcing repair material and synthetic resin (that forms a film of paint applied to color layers in the past). For white wall paintings of Heungguk temple, it was possible to settle permanently by using glue on reinforcing repair material and synthetic resin (that forms a film of paint applied to color layers in the past).

| Table 1. Current State of Adhesives used in Buddhist mural paintings. |
|---|---|---|---|
| '74-'99 | Year | Adhesive | '00-'10 | Year | Adhesive |
| Buddhists mural painting | Geungnakjeon Hall of Muswa Temple | 1974-1985 | Acrylic emulsion 8%, Isocyanate PNSY 6% 5% | 18 | Eungjindang Hall of Mihwangsa Temple | 2000 | Primal MC76 in water 3-7% |
| 2 | Ulghwara Pavilion in Hwaamsa Temple | 1981 | Acrylic emulsion or Isocyanate PNSY6 | 19 | Siwangjeon Hall of Eunhasa Temple | 2000 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 3 | Myeongbokjeon Hall of Sada Temple | 1981 | Acrylic emulsion or Isocyanate PNSY6 | 20 | Daeungjeon Hall of Bongeolgsa Temple | 2000 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 4 | Geungnakjeon Hall of Daewonsa Temple | 1982 | Acrylic emulsion or Isocyanate PNSY6 | 21 | Daegwangjeon Hall of Sinheungsa Temple | 2001 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 5 | Eungjinjeon Hall of Bulyeongsa Temple | 1984 | Acrylic emulsion or Isocyanate PNSY6 | 22 | Daeungjeon Hall of Gwalryongsangsa Temple | 2002 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 6 | Yaksajeon Hall of Gwalryongsangsa Temple | 1984 | Acrylic emulsion or Isocyanate PNSY6 | 23 | Geungnakjeon Hall of Bongeolgsangsa Temple | 2002 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 7 | Musajeon Hall of Heungguksa Temple | 1984 | Acrylic emulsion or Isocyanate PNSY6 | 24 | Josadang Hall of Buseoksa Temple | 2002 | Animal glue in water 1-2% |
| 8 | Josadang Hall of Buseoksa Temple | 1985 | Paraloid B-72 in toluene 1-8% | 25 | Geungnakjeon Hall of Daejoeoksa Temple | 2004 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 9 | Gakhwangeon Hall of Hwaeomsa Temple | 1986 | Paraloid B-72 in toluene 1-8% | 26 | Yeongsanjeon Hall of Songgwangsa Temple | 2005 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 10 | Daegwangjeon Hall of Sinheungsa Temple | 1988 | Paraloid B-72 in toluene 1-8% | 27 | Geungnakjeon Hall of Muwhisa Temple | 2005 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 12 | Gwaneumjeon Hall of Songgwangsa Temple | 1993 | Paraloid B-72 in toluene 3-10% | 29 | Yaksajeon Hall of Gwalryongsangsa Temple | 2008 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 13 | Daeguneujeon Hall of Bogwansa Temple | 1993 | Paraloid B-72 in toluene 3-10% | 30 | Baekheungam of Eunhaesa Temple | 2008 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 14 | Daeguneujeon Hall of Daegoksa Temple | 1996 | Paraloid B-72 in toluene 3-10% | 31 | Daeungjeon Hall of Sanggyesa Temple | 2008 | A emulsion 60% Poly vinyl acetate in water 1-3% |
| 15 | Daeguneujeon Hall of Sanggyesa Temple | 1998 | A emulsion 60% Poly vinyl acetate in water 1-3% | 32 | Nahaneon Hall of Seonghyeolsa Temple | 2010 | Animal glue in water 1-2% |
| 16 | Daeguneujeon Hall of Naesosa Temple | 1999 | A emulsion 60% Poly vinyl acetate in water 1-3% | 33 | Bogwamnyeongjeon Hall of Wibongsa Temple | 2010 | Animal glue in water 1-2% |
| 17 | Daeguneujeon Hall of Jeonghyesa Temple | 1999 | A emulsion 60% Poly vinyl acetate in water 1-3% | 34 | Daeungbojeon Hall of Naesosa Temple | 2010 | A emulsion 60% Poly vinyl acetate in water 1-3% |
5. Conclusion

For some time, reinforcing agents have been used as a way of preserving aged and damaged wall paintings. It was known with the appropriateness of material and method of conservation at that time. When it comes to the application and selection of material in conservation treatment, it is mandatory that it shall meet the theoretical requirements based on a number of experts’ experiences. However, as before, it is difficult to absolutely conclude that currently applied material or technology is always the best.

There are various damages in different types on wall paintings in Buddhist temples. Some of them are irrevocable due to excessive artificial conservation treatments. There are some of which damage is extensive. However, the basic material and structure of wall paintings are still well preserved. This indicates that trial and error in the past would repeat, by sticking with the same method of choosing conservation material that is strong and lasting.

While neither having thorough review on conservation material selection and suitability and nor carrying out researches on material characteristics of wall paintings, the results from conservation treatment in the past cannot overcome inherent problems. Accordingly, there found no effective measure to remove pre-treatment materials until now. More recently, there have been trials and efforts to find more stable conservation methods and also to find alternatives in material selection by conducting scientific tests on material characteristics and conservation materials. More in detail, researches are making breakthroughs in finding the effectiveness and application of color-layered binder and wall reinforcement.

The best method of preserving wall paintings of Buddhist temples is to minimize intervention and to proactive conservation, based on how previous conservation were carried out in the past. It is impossible to permanently preserve wall paintings with only a single conservation treatment. Therefore, it is a must to continue the researches on technology and conservation materials, along with regular maintenance.

References

Seismic Structural Monitoring of the World Heritage Stone Monument after the Central Java Earthquake of 2006, Indonesia

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Abstract

The heritage stone structures of the local andesite blocks, composing Prambanan World Heritage Temples in Indonesia originated in the 9\(^{th}\) century. Although they had been ruined during their long histories, the structures were reconstructed in the 20\(^{th}\) century (Candi Siva was reconstructed first by Dutch engineers in the middle of 20\(^{th}\) century; the other buildings were reconstructed by Indonesian engineers during the end of 1980s and beginning of 1990s). In 1991, those architectural heritages were registered as World Heritage by UNESCO. From a structural point of view, it should be taken into account that the structure composed of the inner concrete structure and the exterior stones, because they were reconstructed by applying the modern structural technology utilizing reinforced concrete technique. The Central Java earthquake of May, 2006 caused severe damage to those World Heritage Prambanan Temple Compounds. For proposing the restoration plan, Japanese experts have been involved in the architectural structural survey in corporation with Indonesian experts. In order to assess the structural seismic safety, the structural monitoring, earthquake and crack displacement, has been successfully conducted as an international collaborative project. The main scope of the present paper is to show the seismic behaviors on the basis of the earthquake data, recorded on 21\(^{st}\) September 2010, on 24\(^{th}\) November 2011 and on 19\(^{th}\) March 2012 at Candi Siva, the largest structure of the Prambanan Temples. The earthquake response analysis was also conducted to simulate the dynamic response to the event of September 2010. In the present analysis model, dynamic soil-structure interaction phenomenon was taken into account under the condition that the structure was so massive and comparatively rigid. The analysis demonstrated that the soil-structure interaction had significant effect on the dynamic structural response. Moreover, the structural stability was discussed on the basis of the crack and temperature monitoring data.

Keywords: Stone masonry, Earthquake damage, Structural monitoring, World heritage, Analysis

1. Introduction

A devastating earthquake of magnitude 6.4 that hit Central Java in Indonesia on 27th May 2006 affected a number of architectural heritages in the area of Yogyakarta, one of the historic cities in Indonesia. This near field earthquake caused serious damage to the Prambanan Temple Compounds, World Heritage, being located 25km from the epicentre(Japan Center for International Cooperation in Conservation, National Research Institute for Cultural Properties, Tokyo 2008). For proposing the restoration plan, Japanese team has been involved in the
architectural structural survey of the earthquake damage as an international collaborative project since just after the earthquake. In this international project, seismic structural monitoring has been conducted to understand the actual seismic behaviours of the structure, as well as, to assess the structural seismic safety. As structural seismic monitoring, earthquake and crack/temperature have been monitored.

The present study deals with the Siva Temple of which height is 47m, the largest one of 8 monuments of the Prambanan Temple. This apparently masonry structure is characterized by the composite one combining the inner reinforced concrete covered by the exterior andesite stone walls with decorative ratona/stupa stones. Such composite structure was introduced when the monument was reconstructed by Dutch engineers in 1950’s. However, the inner structural condition of the Siva Temple has been unknown so far, although that of the other monuments in the Prambanan site was described in the drawings at the reconstruction in the end of 1980’s.

2. Earthquake Monitoring

It is essential to understand the actual seismic behaviours of Prambanan Temple, as the inherent characteristics of the earthquake response should be considered to discuss the restoration plan. Monitoring of earthquake response was started at Candi Hangsa in October 2007. However, the restoration works started at Candi Hangsa in July 2010, therefore, it was needed to remove the seismograms at Candi Hangsa at that time. After new monitoring system was re-installed at Candi Siva, earthquake monitoring was restarted there. Shown in Figure 1, strong-motion seismograms, were installed at 4 points, Top, Middle, Base and Ground. Three components of EW, NS and UD at every point have been recorded.

During the earthquake monitoring period, three earthquakes occurred in the vicinity of Yogjakarta on September 12th 2010, November 24th 2011 and March 19th 2012, listed in Table 1. It can be noticed in this table that the focal depth of 2010 events was much deeper than those of 2011 and 2012 events. The earthquake data of those events were successfully recorded at Candi Siva. The acceleration response spectra of the ground motions of those earthquakes are shown in Figure 2. The predominant period of response spectra (See Figure 2), the seismic response displacement (See Table 2) and the natural frequencies (See Table 3) show that the characteristics of the ground motions of 2010 are different from both those of 2011 and of 2012. These records show that the natural frequency of soil-structure system was slightly affected by the ground motion characteristics. Furthermore, they show that the natural frequency become longer with increase of the response displacement.
3. Monitoring of crack displacement with temperature

A lot of cracks were generated at the exterior stone walls and around the entrances to the inner chambers by the Central Java Earthquake of 2006. Long term monitoring of these cracks has been conducted to assess structural stability of the monument, at the same time, to make clear the relation between crack displacement and variation of temperature. Therefore, monitoring of crack and temperature has been conducted since October 2008. At the same time, the humidity has been monitored with temperature.

Table 1. Three Earthquakes Recorded.

<table>
<thead>
<tr>
<th>Day</th>
<th>Local Time</th>
<th>$M_L$</th>
<th>Depth (km)</th>
<th>Epicentral Distance (km)</th>
<th>MMI</th>
<th>PGA (cm/s$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 12$^{th}$ 2010</td>
<td>23:37</td>
<td>5.0</td>
<td>48</td>
<td>11</td>
<td>IV</td>
<td>8.6</td>
</tr>
<tr>
<td>Nov. 24$^{th}$ 2011</td>
<td>10:55</td>
<td>5.1</td>
<td>10</td>
<td>165</td>
<td>III</td>
<td>1.8</td>
</tr>
<tr>
<td>Mar. 19$^{th}$ 2012</td>
<td>9:19</td>
<td>4.2</td>
<td>10</td>
<td>40</td>
<td>III</td>
<td>9.1</td>
</tr>
</tbody>
</table>

$M_L$: Local magnitude, MMI: Modified Mercalli Intensity scale estimated by PGA, PGA: Peak Ground Acceleration

Table 2. Peak of Response Displacement (Top, Ground) and Amplitude Factor.

<table>
<thead>
<tr>
<th></th>
<th>Sep. 12$^{th}$ 2010</th>
<th>Nov. 24$^{th}$ 2011</th>
<th>Mar. 19$^{th}$ 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX.</td>
<td>min.</td>
<td>MAX.</td>
</tr>
<tr>
<td>EW Top</td>
<td>0.18</td>
<td>-0.22</td>
<td>0.02</td>
</tr>
<tr>
<td>EW Ground</td>
<td>0.06</td>
<td>-0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>NS Top</td>
<td>0.02</td>
<td>-0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>NS Ground</td>
<td>0.02</td>
<td>-0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>EW</td>
<td>2.33</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>1.14</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Figure 2. Comparison of Acceleration response spectra of ground motions.
Table 3. Natural Frequency Evaluated by Transfer Function.

<table>
<thead>
<tr>
<th></th>
<th>Natural Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>/ground</td>
<td></td>
</tr>
<tr>
<td>EW</td>
<td>1.95</td>
</tr>
<tr>
<td>NS</td>
<td>1.99</td>
</tr>
<tr>
<td>/base</td>
<td></td>
</tr>
<tr>
<td>EW</td>
<td>2.93</td>
</tr>
<tr>
<td>NS</td>
<td>2.67</td>
</tr>
</tbody>
</table>

Shown in Figure 3, crack displacement has been monitored by using Pi-type displacement gages at 14 points (See Figure 3) in the inside rooms and on the outside stone wall of Candi Siva. In addition, 4 pieces of dummy displacement gages were installed just nearby the displacement gages on the outside stone wall. Monitoring of temperature and humidity has been conducted by using temperature-humidity loggers in each inner chamber. Monitoring of temperature using thermocouple has been conducted at 2 points, outside and in the central inner chamber. Data logger was put at the central inner chamber and was connected to both the thermocouples and to the Pi-type crack gages.

Monitoring of crack displacement has been conducted since October 29th 2008. As well as, monitoring of temperature with humidity has been carried out. The present paper describes the movement of crack displacement and temperature before and after every earthquake. Since the crack displacement was affected by temperature, crack displacement records were corrected to account for the effect of the variation of temperature. Correlation between movement of crack displacement and variation of temperature should be noticed (See Figures 4 and 5). Furthermore, these figures show that the movement of crack displacement was not caused at the occurrence time of the earthquake. As these earthquake ground motions were so small, these monitoring records indicated the structural stability of Candi Siva at the present state.

![Figure 3. Location of equipment installed at Candi Siva.](image-url)
4. Earthquake response analysis using simplified model

A simplified analysis model, lamped masses models, were introduced to simulate the seismic response. By employing the proposed models, the natural period and the vibration mode were evaluated and compared with the earthquake record. For proposing the structural restoration plan, such simulation analysis was so useful not only to understand the actual behaviours but also to evaluate the earthquake resistance of the structure.

In the present earthquake response analysis, it was employed the simplified model considering soil-structure interaction to simulate the seismic behaviours of the event on September 12th, 2010. The structure of the Siva Temple was idealized by a stick model with 6 masses connected by beam elements. In addition, the 3 types of models were assumed as:

A) Rigid base model without dynamic soil-structure interaction
B) Sway-rocking (it is called SR) model, without base embedding effect
C) Embedding SR model, with base embedding effect. Among the above models, dynamic soil-structure interaction was taken into account in both B) SR model and C) embedding SR model.

Not only eigenvalue analysis but also seismic response analysis was performed on the assumption that the structural material was concrete, as the inner structure was reconstructed by reinforced concrete technique. Such simplified model might be useful for the structure of which inner structural condition was not known. Here, it was ignored that the andesite stones were used for exterior walls. In this seismic response analysis, Rayleigh damping model for the whole system was assumed to be 4% (both for the primary and secondary modes). In addition, damping ratio of the soil spring was assumed to be 7%. Depth of embedding base was assumed to be 8m. In the present study, the soil spring stiffness was evaluated by employing the approximate solution of the vibration admittance theory (The Japan Electric Association 1992). Material properties of concrete were evaluated from the experimental report of the laboratory material test of concrete samples, which was conducted in Gadjah Mada University.

Table 6 compares the natural frequency of the analysis models with that of the earthquake monitoring.
records. Figure 14 also compares the analyses with the observation, where the peak acceleration of the seismic response is described. It should be noticed in Table 6 and Figure 7 that the peak response acceleration of the embedding SR model is the closest to the actual record. Furthermore, the acceleration waveforms and the transfer function of the embedding SR model was well correlated with the record. Hence, for comparison of record and analysis, the observation points at Top (h=37.2m) and Middle (h=23.9m) correspond to the mass’s number No.6 (h=40.2m) and No.4 (h=22.0m), respectively.

As results, Table 6 shows natural frequency of the analysis models in comparison with the observation. It can be noticed that the natural frequency of the base fixed model is rather higher than that of the SR models introduced to take into account soil-structure interaction. Furthermore, the natural frequency of SR model with embedment spring is in good agreement with the observation. Shown in Figure 7, the maximum response acceleration of embedding SR model is in better agreement with that of the monitoring record, although the maximum response acceleration of the fixed base model at mass No.6 is much larger than the record. As results of the present study, it was made clear that dynamic soil-structure interaction greatly affects the seismic response of such massive and rigid structure on the soils. The acceleration response wave forms of the analysis and the monitoring showed that the wave forms were in good agreement. The peak value of transfer function from the ground to the top was at 2.0Hz. On the other hand, the peak value of transfer function from the top to the base is at 3.0Hz. It demonstrated that the natural frequency of soil-structure system was lower than that of structure itself. These made it clear that soil-structure interaction greatly affects the seismic performance of this monument. In the present project, 3-D FE model was also employed to simulate the seismic behaviours of Candi Garuda, one of the monuments of the Prambanan (Toshikazu Hanazato et al. 2010). 3-D finite element model demonstrated that the inner structure would not be damaged even by the large earthquake of 2006.

![Figure 6. Three types of analysis models.](image-url)
Table 6. Comparison of natural frequency.

<table>
<thead>
<tr>
<th>Analysis Model</th>
<th>Natural Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Base Fixed Model</td>
<td>4.6</td>
</tr>
<tr>
<td>B) SR Model</td>
<td>1.6</td>
</tr>
<tr>
<td>C) Embedding SR Model</td>
<td>2.0</td>
</tr>
<tr>
<td>Monitoring</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Figure 7. Comparison of peak response acceleration.

5. Concluding remarks

The earthquake data of three events have been successfully recorded since the installation of the equipment at Candi Siva. As the magnitude of the recorded three earthquakes was as small as 4.2 through 5.1, the ground motion level was less than 10cm/s² in PGA. However, those monitoring data revealed the fundamental dynamic characteristics of the earthquake response. Those data showed that the natural frequency observed during the earthquakes corresponded to that of the micro tremor measurement, because the ground motion level of those earthquakes was not high enough to cause non-linearity of both the structure and the soil-structure interaction. Utilizing the earthquake monitoring data, simulation analysis was successfully performed. The simulation analysis using the simplified model made it clear that soil-structure interaction greatly affected the seismic performance of Candi Siva, indicating that the dynamic performance of such massive structure is rather affected by the soil-structure interaction. To assess the seismic safety, the simplified lumped masses model was useful for such heritage structures of which inner structural condition was unknown.

The monitoring records showed that the crack displacement was affected by temperature. However, the long term monitoring of crack displacement for about 4 years at Candi Siva indicated that the structure has been stable, as there found no significant crack movement even when the earthquake occurred in September 2010, November 2011 and March 2012.

Acknowledgements

The authors wish to express their sincere gratitude to the government of Indonesia Ministry of Culture and Tourism Directorate General of History and Archaeology, the preservation office of Archaeological Site
Yogyakarta Special District, the staff responsible for field office for their generosity and help, without which this experiment would have been realized.

References


**Restoration of Kodokan Stone Monument Damaged by the Great East Japan Earthquake**

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**Abstract**

The Kodokan, opened in August 1841 as the Mito clan’s school. The Kodokan stone monument is made of marble called Kansuiseki. The spirit of Kodokan is curved on the surface of the stone monument. The Great East Japan Earthquake of 9.0 magnitude occurred in March 11, 2011. The stone monument collapsed due to the ground movement of the earthquake. After this, the Agency for Cultural Affairs organized a committee of experts for the restoration project. First, the investigation was carried out to identify the cause of the damage. The following procedures were decided by the committee of experts for the restoration. The stone monument was strengthened by using stainless steel bolt, Aramid fiber and epoxy resin. The broken surface stones with inscription were returned to the original position and strengthened with inorganic adhesive. The restoration program was completed at fall in 2013.

**Keywords**: Stone monument, Earthquake damage, Restoration, Stability

1. **Introduction**

The Kodokan, which opened in August 1841, served as the Mito clan’s school for the feudal domains. Feudal warriors and their children attended the Kodokan, where the admission age was 15 and there was no graduation or completion age. Both traditional and academics and military art were emphasized at the school, which also had one of the nation’s best premises. Similar to modern university, the kodokan had academic halls like Seicho and the Nobility hall where students learned traditional subjects, on artistic wing for learning military arts, as well as medicine, astronomical observatory, racecourses for horseback riding, and an area for military training. The section where the Eight trigrams hall, Kashima shrine, and Confucian temple were built was considered sacred grounds. At the academic halls, students learned subjects like Confucianism, history, astronomy, mathematics, and music. Subjects like fencing, spearing, military strategy, and equestrian skills were taught in the artistic wing of the school (Ibaraki Prefecture, 2014).

The spirit of the foundation of Kodokan school was stated by Tokugawa Nariaki, ninth Daimyo of Mito Domain. This statement was engraved on the marble stone called Kansuiseki in Japanese. The stone monument consists of the body and pedestal, and the body is rectangular column 328.5 cm in height, 193 cm in width and 58.3 cm in thickness. The Eight trigrams hall was built as a shelter of the stone monument. Figure 1 shows the outside view of the Eight trigrams hall.

The Great East Japan Earthquake of 9.0 magnitude occurred in March 11, 2011. The stone monument collapsed due to the ground movement of the earthquake. The Agency for Cultural Affairs organized a committee of experts for the restoration project. This paper reports the investigation to identify the cause of the damage and restoration process of the stone monument.
2. Damage of the stone monument due to the Great East Japan Earthquake

The Great East Japan Earthquake of 9.0 magnitude occurred offshore Miyagi prefecture on March 11, 2011. Figure 2 shows the location of the epicenter of the earthquake and the location of Mito city where Kodokan is located in Japan (Japan ICOMOS, 2012). 744 cultural properties, including nationally designated ones, were reported as damaged (Agency for Cultural Affairs, 2012). In Mito city where Kodokan is located, the ground vibration of 325.7 gal was recorded. One photo of the damaged stone monument is shown in Figure 3. The middle and lower parts of the stone monument were heavily damaged by the earthquake. At some points, the width of the crack reached 3 cm even though stone blocks were not fallen down. The stone monument tilted forward about 4 cm. Some space was observed between the body base of the stone monument and the mortar cover of the pedestal stone. Schematic diagram of the cross section of the damaged monument is shown in Figure 4.

The detailed investigation of the severely damaged monument, the following factors were considered as important causes for the damage. In 1945 at the end of World war II, the Eight trigrams hall burnt down by the air raid. At that time, stone monument suffered high temperature and many cracks appeared in the body of the monument and this decreased its strength. It was also found that the impregnated epoxy resin did not reach the deep portion during the restoration work in 1972. In order to increase the stability of the body of the monument, concrete plate was attached at the back side of the stone monument.

Though this concrete prevented fall down of the monument at the Great East Japan earthquake, the concrete plate acted to increase the overturning moment of the monument. This increased the stress concentration of the lower part of the monument and led the collapse of the monument.

3. Restoration of the stone monument

3.1. Restoration method

The Agency for Cultural Affairs organized a committee of experts for the restoration project (Uchida, 2014). The experts thought that it was difficult to move this monument to the facility for the restoration and planned to restore the monument on site and put the seismic isolation table beneath the monument after the restoration work was completed since the stone monument was damaged so severely. In order to install the base for seismic isolation table, the ground under the stone monument was investigated. This test excavation revealed that the
original compacted earthen base which was built during the foundation of the monument remained in a good condition. The committee for the restoration project decided not to excavate the ground for the installation of the base of the seismic isolation table, because this would damage the original compacted earthen base. Next an alternative method was proposed to install the seismic isolation table between the body of the monument and the pedestal. But in this case the location of the body of the monument would be changed by the thickness of the seismic isolation table. The committee for the restoration project also decided not to adopt this alternative method. The committee finally decided to relocate the monument to the facility for restoration and strengthen the monument sufficiently and increase the degree of quakeproof structure without using the seismic isolation table.

In order to strengthen the stone monument, it is necessary to clarify the present condition of inside cracks. Based on the detailed study of these cracks, it was found that the some inside cracks reached the bottom of the body of the monument. In addition, iron blocks were found between the body and the pedestal of the monument. Based on these investigations, the committee for restoration decided to remove the concrete plate behind the stone monuments which was attached during the restoration in 1972 to reduce the unstable condition and strengthen the body of the monument. It would be possible to get more stable condition of the structure as those of the original condition by following those procedures.

![Figure 3. Damaged Kodokan stone monument due to the Great East Earthquake.](image1)

![Figure 4. Schematic diagram of the cross section of the damaged stone monument.](image2)

![Figure 5. Schematic diagram of the cross section of the stone monument planned for the restoration.](image3)

![Figure 6. Schematic diagram of the cross section near the surface with inscription planned for the restoration.](image4)
In addition, analysis of the overturning moment of the monument was carried out to increase the stability against earthquake. From this analysis, it was concluded that the stability would increase when the body of the monument and the pedestal were strengthened and then firmly attached together as shown in Figure 5. The Aramid fiber sheet was utilized for strengthening the body of the monument during this procedure.

Figure 6 shows the schematic diagram of the cross section near the surface with inscription planned for the restoration. At first, the inside of the body of the monument was strengthened by injecting epoxy resin into the cracks. Then the surface was made to be flat by applying cast stone on the cracked surface. The Aramid fiber sheet was put on the smooth surface to strengthen the monument. The surface stone with inscription was located on the Aramid fiber sheet and attach with epoxy resin paying great attention to return it to its original position.

3.2. Restoration procedure

The restoration was carried out step by step in the following procedure after the occurrence of the Great East Japan Earthquake (Agency for Cultural Affairs, 2013).
1) Investigation and documentation of the condition of the damage and collection of the stones fallen down
2) Test excavation of the ground under the monument for the investigation of the ground condition
3) Planning of the restoration procedure
4) Lifting up the Eight trigrams hall and move the stone monument to the restoration facility
5) Restoration treatment of the monument
   a. Body of the monument; Strengthen the cracked part by injecting epoxy resin into these cracks
   b. Stones fallen down; Slice cutting of the surface stone with inscription to around 5 cm thickness
   c. Backside concrete plate; Remove the backside concrete plate and strengthen the original stone by applying the Aramid fiber sheet
   d. Pedestal; Investigation of the condition of the pedestal and remove the mortar cover layer and strengthen the original stone with epoxy resin and inorganic adhesive
6) Integration of the fallen stone and the body part of the monument by locating the surface stones with original position
7) Lifting up the Eight trigrams hall and move the stone monument to the original position in the Eight trigrams hall
8) Integration of the body and the pedestal of the monument

3.2.1. Restoration of the body of the monument

The severely damaged stone in the lower part of the monument was temporary removed from the main body part. The cracks and voids were also found at the higher part of the body. Epoxy resin with middle level viscosity was injected into these cracks to strengthen the body of the monument. When the temporary removed

Figure 7. Stainless bolt was inserted in the drilled hole and fixed by injecting epoxy resin into the hole.

Figure 8. Surface condition with inscription after the restoration.
stone blocks were attached to the body, stainless bolts were inserted in the drilled hole and fixed by injecting epoxy resin into the hole. This is shown in Figure 7.

On the backside of the body, the concrete plate which was placed for strengthening the body during the restoration in 1972 was removed. Then the cracked parts were strengthened with injecting epoxy resin into these cracks. The Aramid fiber sheet with high tensile strength was applied on the back surface and the surface was covered with cast stone which was made of marble powder, calcite powder and acrylic emulsion. Finally the surface was smoothed with sand paper.

Stone blocks with inscription on the surface were sliced to about 5 cm from the surface. The Aramid fiber sheet was applied to the base surface where the sliced stones with inscription were located in order to strengthen the body of the monument. As a next step, the sliced stones were located at the original positions by checking their positions before the collapse at the Great East Japan earthquake. The missing part of inscription was finished with cast stone. To identify the restoration of missing part, the surface level was lowered slightly by 3 mm than the original surface. This is shown in figure 8.

3.2.2. Restoration of the pedestal of the monument

On the surface of the pedestal mortal was applied to strengthen the pedestal during the restoration in 1972. The committee for restoration decided to remove the mortar on the surface and show the original surface of the marble stone of the pedestal. In order to clarify the present condition, surface mortal layer was removed. Then, it was found that the marble stone of the pedestal was damaged by the fire caused by the air raid in 1945. The cracked parts were strengthened by using epoxy resin and missing part was finished with cast stone. The body and the pedestal of the monument were glued tightly together by using epoxy resin to increase the seismic stability. The restoration was completed in November 18, 2013. Figure 9 shows the Kodokan stone monument after the restoration work.

Figure 9. Kodokan stone monument after the restoration work.
4. Conclusions
The Great East Japan Earthquake of 9.0 magnitude occurred in March 11, 2011. The stone monument of Kodokan in Mito city collapsed due to the ground movement of the earthquake. After this, The Agency for Cultural Affairs organized a committee of experts for the restoration project. First, the investigation was carried out to identify the cause of the damage. The restoration was carried out to strengthen the stone monuments by installing concrete plate behind it during the restoration in 1972. The research results revealed that the installation of concrete plate behind the stone monument at the previous restoration had a bad effect during the vibration due to the earthquake. The following procedures were decided by the committee of experts for the restoration. The stone monument was moved to the restoration facility and the concrete plate was removed. The stone monument was strengthened by using stainless steel bolt, Aramid fiber sheet and epoxy resin. The broken surface stones with inscription were returned to the original position and strengthened with inorganic adhesive. The mortar cover of stone pedestal applied at the previous restoration was removed and strengthened by using epoxy resin. In order to make the stone monument anti earthquake structure, barycenter of the monument should be lowered and it is necessary to increase the moment to resist against the overturning moment induced by the earthquake force. Based on the results of structural analysis, the stone monument and base stone was firmly glued. The restoration program was completed at fall in 2013.

Acknowledgments
The authors would like to express their sincere gratitude to Agency for Cultural Affairs and Ibaragi Prefecture to allow us to report this work. The authors wish to acknowledge the members of the committee for the restoration of Kodokan monument headed by Prof. Suzuki for helping us to carry out this restoration project.

References
Fundamental Research about Vibration of Stone Lantern (Ishi-toro) by Earthquake

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Abstract

Stone lantern (Ishi-toro) was imported into Japan concurrently with Buddhism and mostly made with construction of the temple. Moreover, the fall and destruction of the stone lantern by an earthquake have been reported by the ancient documents of our country, and those examples become one index of expressing the grade of a shake of the past earthquake. However, the stone lantern designated as a cultural property needs to prevent the fall and destruction by an earthquake, and needs to make the minimum damage to the person at the time of a fall. In this report, it is introduced that the example of damage of the stone lantern by big earthquakes, such as the Great East Japan Earthquake in 2011. Then, the excitation experiment using the reduction model of the stone lantern is conducted, and the result of having worked on the grasp and measure against the earthquake performance of a stone lantern is reported. The damage of the stone lantern in the Great East Japan Earthquake was found even in Tokyo away from the epicenter. From the example, it was found that dry masonry had fallen mostly and the direction where each component was in general the same, the tendency for the direction to shift in a more nearly upper component. Based on these examples, the excitation experiment was conducted using the model made from granite reduced about 40 percent from the usual stone lantern. It was confirmed that dry masonry changed resonance frequency according to the amplitude of uniaxial vibration table. Moreover, in the collapse experiment using JMA Kobe NS wave, dry masonry collapsed with 4 % of 50 % of a time-axis and amplitude, and mortar junction prevented collapse to one 4 times the amplitude of this compared with dry masonry. Furthermore, the specimen of the core stick and the vibrational absorption plastic gel sheet did not collapse.

Keywords: Stone lantern, Earthquake, Vibration table, Acceleration limit for falling, Anti-falling

1. Introduction

The presence of stone lanterns is often mentioned in the records of old documents as one of the indicators expressing the magnitudes of earthquakes that have hit Japan in the past. Many studies are now being conducted to reveal past earthquakes based on the degree of stone lantern falling and damage. It is also a fact that researchers are now focusing on stone lanterns as an effective tool which provides additional information to records of strong earthquakes that have occurred in the past. However, many stone lanterns possess historical and cultural value, and are therefore required to be protected from falling and damage as much as possible in the event of an earthquake. It is also necessary to avoid injuries to people when stone lanterns, which consist of very heavy parts, fall. In reality, however, many stone lanterns are built by simply stacking stone parts without implementing anti-falling measures. As shown in Figure 1, many stone lanterns were fallen over a wide area during the Great East Japan Earthquake in 2011.

These study vibration tests were conducted using small-scale models on large single-axis vibration table in order to study the movement of stone lanterns during an earthquake. In addition to an ordinary stone lantern stacked without reinforcement, three types of reinforced models were prepared and tested using the same vibration test in order to verify their earthquake resistance.
There are no past reports mentioning improvements in the earthquake resistance and falling of stone lanterns. Therefore, this study referred to the outcomes of studies which analyzed the falling and movements of rigid bodies during an earthquake by assuming furniture and other objects as rigid bodies.

a) Ishiyama assumed an object as a rigid body and verified the falling of objects mainly using analytical methods. He developed a program that analyzed the movement in which an object slides and jumps during an earthquake, created formulas, and suggested expressions describing the conditions of falling. He also indicated that in addition to acceleration, the falling of an object required a speed that was higher than a certain level. 1, 2)

b) Kaneko et al. suggested a method to simply evaluate the possibility that furniture or objects may fall during an earthquake. They stated that they could roughly estimate the possibility of the falling of installed furniture during an earthquake if they knew the maximum acceleration and maximum speed of the earthquake, as well as the natural period, damping constant, and a shape of primary mode of a structure. In addition, they indicated that
the falling and the degree of sliding of a rigid body were dependent on the friction coefficient, and the maximum degree of movement was independent of the shape of a rigid body. Furthermore, they obtained the possibility of the falling of a rigid body during an earthquake as a falling ratio and suggested a method to estimate the falling ratio of rigid bodies such as furniture.\textsuperscript{3,4,5,6}

c) Based on falling experiments conducted using a small-scale model of a Buddha statue and acceleration using a single-axis vibration table, Fujita \textit{et al.} indicated that an already established falling limit condition became applicable if the falling of an object with a complicated shape could also be assumed as a rigid body. An acceleration limit for falling is set in the range below a boundary frequency based on a constant acceleration which is a static falling limit.

\[
A_{cr1} = \frac{2}{\pi} \times g \quad \text{\ldots (1)}
\]

Meanwhile, an acceleration limit for falling is set in the range above a boundary frequency using an acceleration based on speed limit.

\[
A_{cr2} = V_{cr} \times (2\pi f) = 1.0 \times \frac{\sqrt{g}}{h} (2\pi f) \quad \text{\ldots (2)}
\]

In Figure 2, which represents these equations in a graph, falling is expected to occur from same-phase locking in zone I, or the range with low frequency, while falling is expected to occur from anti-phase rocking in zone II, or the range with high frequency. In this calculation, \(B\) is the width at the bottom, and \(H\) is twice the height \(h\) of the center of gravity, which can be used for other calculations.\textsuperscript{7)

3. Experimental plan

3.1. Schedule of experiment

The experiment was conducted based roughly on the schedule below:

[January 22, 2013 (Tuesday): First day of the experiment]
- 9:00 to 9:30 Installation of a sample and measuring instruments
- 9:30 to 12:00 Vibration
- 12:00 to 13:00 Break
- 13:00 to 17:00 Vibration

[January 23, 2013 (Wednesday): Second day of the experiment]
- 9:00 to 12:00 Preparation and vibration
- 12:00 to 13:00 Break
- 13:00 to 17:00 Vibration
- 17:00 Cleanup

3.2. Overview of samples

This experiment used an approximately 40\% scale of a Kasuga-type lantern which is the most commonly used type of lantern in shrines and temples. Among the various types of stone lanterns, this lantern is a tall type (about 180 cm), and has a total weight of 800 to 1,000 kg. Lantern consists of six parts including hoju (an orb at the top), kasa (roof), hibukuro (fire compartment), chudai (platform), sao (post), and kiso (foundation). A characteristic feature of Kasuga-style lanterns is the thin and tall sao (post) section. To simplify the production process, decorations which are typically seen in the kasa (roof) section and the hollow space in the hibukuro (fire compartment) were omitted. The sample was made of granite as in the case of actual lanterns.

Four types of samples shown in Table 1 and Figure 3 were prepared in this experiment to compare differences in movement during an earthquake, which are dependent on the methods of reinforcement. The four types of samples were of the same size. Sample A was made by simply stacking components, which is the most common structure. Sample B was made by adhering components together with mortar. Sample C was made by
creating a hole in the center of each component, through which a core bar was inserted from the foundation to the *kasa* and from the *kasa* to the *hoju*, and the components were adhered together with an elastic adhesive. Sample D was made by placing multiple layers of plastic gel sheets between components and adhering them together with a special adhesive. Sample B in which mortar was used between the components and samples C and D in which adhesives were used were left for one week by the vibration test as a drying period after they were completed.

### 3.2.1. Calculation of the height of the center of gravity

The acceleration limit for falling is correlated with the shape factor. When an object possesses a complicated shape, its shape factor is calculated by the width of the bottom and by multiplying the height of the center of gravity by two. Studies and investigations of falling during past earthquakes have revealed that when Kasuga-style lanterns were simply stacked without adhesive, the lanterns fallen from the unstable *sao* (*post*) sections which were placed on stable foundations with large bottom areas. Therefore, this study calculated the height of the center of gravity as follows in two separate cases including a case in which the *sao* and the sections above fallen together (left in Figure 4) and a case in which the entire lantern including the foundation fallen (right in Figure 4). Table 3 shows the outcomes of the calculations of the center of gravity in each case. This paper describes the first case as “stacking without adhesive” from here on.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Reinforcement (Yes/No)</th>
<th>Construction method</th>
<th>Reduced scale (mm)</th>
<th>Height (mm)</th>
<th>Height of center of gravity (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>No</td>
<td>Dry masonry</td>
<td></td>
<td>700</td>
<td>383.11</td>
</tr>
<tr>
<td>B</td>
<td>Yes</td>
<td>Bonding by mortar</td>
<td>About 302.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Yes</td>
<td>Core bar with adhesive</td>
<td>40% 302.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>Vibration absorbing gel with adhesive</td>
<td>40% 302.57</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.** Original Kasuga-toro (A) and reduced scale model for this test (B).
(i) As shown in Figure 5 and Figure 6, the mass of each component of a stone lantern is estimated, and a multi-body system model is created.

(ii) The height of the center of gravity is calculated using the following equations.

\[ \sum_i m_i = M \ldots (3) \]

\[ h = \frac{\sum_i m_i h_i}{M} \ldots (4) \]

Here, “\( m_i \)” is the mass at the cross-section \( i \), “\( M \)” is the overall weight, “\( h_i \)” is the height of a cross-section, and “\( h \)” is the height of the center of gravity.

**Figure 4.** Specifications of each sample.

**Figure 5.** Cases of falling stone lantern.

**Figure 6.** Prediction procedure of height of center of gravity (A: dry masonry, B: integrated).
3.2.2. Acceleration limit for falling

Table 2 shows the acceleration limit for falling, shape factor \( B/H \), and boundary frequency \( f_0 \) for a lantern stacked without adhesive and an adhered lantern. Figure 7 is the graph of the acceleration limit for falling. These values indicate that the possibility of falling occurs for a lantern stacked without adhesive when the acceleration is 162.0 gal or higher. Meanwhile, lanterns with adhered components are estimated to withstand about 2.8 times greater acceleration than a lantern stacked without adhesive. Also, statically speaking, falling from same-phase locking which is said to occur at a frequency below the boundary frequency requires a displacement amplitude (total amplitude) that is greater than half of the bottom width \( (B/2) \). Therefore, the possibility of falling from same-phase locking occurs when there are vibrations which oscillate for 5.5 cm or more for lanterns stacked without adhesive and 14 cm or more for lanterns with adhered components.

### Table 2. Calculation result of fall limit acceleration, shape coefficient \( B/H \) and boundary frequency \( f_0 \)

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Dry masonry ( f_0 = 2.0 )</th>
<th>Integrated ( f_0 = 1.9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>162.0</td>
<td>453.9</td>
</tr>
<tr>
<td>1.0</td>
<td>162.0</td>
<td>453.9</td>
</tr>
<tr>
<td>2.0</td>
<td>169.3</td>
<td>453.9</td>
</tr>
<tr>
<td>3.0</td>
<td>253.9</td>
<td>678.1</td>
</tr>
<tr>
<td>4.0</td>
<td>338.5</td>
<td>904.2</td>
</tr>
<tr>
<td>5.0</td>
<td>423.2</td>
<td>1130.2</td>
</tr>
<tr>
<td>6.0</td>
<td>507.8</td>
<td>1356.3</td>
</tr>
<tr>
<td>7.0</td>
<td>592.4</td>
<td>1582.3</td>
</tr>
<tr>
<td>8.0</td>
<td>677.1</td>
<td>1808.3</td>
</tr>
<tr>
<td>9.0</td>
<td>761.7</td>
<td>2034.4</td>
</tr>
<tr>
<td>10.0</td>
<td>846.3</td>
<td>2260.4</td>
</tr>
</tbody>
</table>

**Figure 7.** Calculation result of limit acceleration for falling.

### 3.3. Vibration plan

Table 3 shows the list of the main waves that were applied. Vibration was applied to Sample A by adjusting the amplitude of the JMA Kobe NS wave after obtaining resonance frequencies using harmonic sine waves and comparing how the resonance frequency changed based on amplitudes. There was a possibility that the strength of the adhered sections of Samples B, C, and D might be reduced by vibration. Therefore, the JMA Kobe NS wave was first applied to these samples, and vibrations were continued to be applied until collapse occurred or the amplitude reached 20%. In addition, since there was a high possibility of falling of samples due to vibrations caused by heavy weight of the stone, in order to prevent damage to the vibration table from falling sample parts, a box with the dimensions 1,200 by 1,700 mm and a height of 300 mm, and a wooden platform to secure the box to the vibration table were constructed. 24 mm plywood was used for the bottom of the box, and 15 mm plywood was used for the walls. In addition, the inside of the walls was lined with 30 mm Styrofoam sheets as protection. Moreover, vibrations were applied after connecting the three components of lanterns (hoju, kasa, and hibukuro) to a movable crane with nylon ropes with extra lengths to avoid affecting the movements of lanterns during the application of vibrations.

Also, in order to recreate the environments in which stone lanterns are usually installed, sand was placed and compacted inside the box to a height of about 30 mm. When installing a new sample or when a sample sank into the sand due to the vibrations applied immediately before, a sample was re-installed at the center of the box each time after compacting the sand using boards and hammers, and marking the sand using strings strung between nails on the walls of the box and a plumb bob in order to obtain accurate displacements and achieve consistent ground conditions as much as possible. Leveling was also verified each time after compacting the sand and installing a sample.
3.4. Measurement plan

This experiment included measurements of acceleration, measurements of displacement using three-dimensional image measurements, and recording using video cameras.

3.4.1. Measurement of acceleration

ARF-100A accelerometers (Tokyo Sokki Kenkyusho) were used in this experiment. Since the surfaces of the samples were uneven, accelerometers were attached to samples using double-sided tape and masking tape over the top of the accelerometer. The right-hand side facing the attached surface was considered positive, and CH 1 to 6 were attached to each component of a sample, and CH 7 to the vibration table. Figure 8 shows the attached positions.

3.4.2. Three-dimensional image measurement

Two high-speed cameras captured and recorded the movements of high-intensity LED markers attached to samples. Figure 9 shows the positions of the cameras and the marker numbers.

<table>
<thead>
<tr>
<th>Table 3. Cases of input wave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample No</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Figure 8. Installation points of accelerometer.
4. Outcomes of the experiment and observations

4.1. Findings of the measurements of acceleration

4.1.1. Harmonic sine waves

In this part of the experiment, harmonic sine waves were applied while making fine adjustments to the amplitude and frequency, and the resonance frequency of each sample was obtained. Table 4 shows the outcomes. These outcomes indicate that changes in the amplitude result in changes in the resonance frequency. Figure 10 shows a comparison of these outcomes with the graph of the acceleration limit for falling. Here, all vibrations are much lower than the acceleration limit for falling, verifying that no falling occurs.

Also, a harmonic sine wave with an amplitude of 100 mm and a frequency of 1.8 Hz, which is equivalent to Zone I in Figure 2, was applied to generate vibration in order to study the conditions of falling of Sample C as an object in which all components were unified. Although the sample slid significantly, it did not fall despite being in a falling zone. Since loose compacting of the sand below the sample is thought to be the cause of this outcome, it is difficult to apply falling acceleration limit predictions in some ground conditions.

Table 4. Results of resonant frequency of each sample.

<table>
<thead>
<tr>
<th>Input wave</th>
<th>Sample No</th>
<th>Amplitude (mm)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonic sine wave</td>
<td>A</td>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>1.8</td>
</tr>
<tr>
<td>C</td>
<td>1.5</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>3.0</td>
<td>4.2</td>
<td></td>
</tr>
</tbody>
</table>

4.1.2. JMA Kobe NS Wave

Table 5 summarizes the input waves and the magnitudes of amplitude at which falling occurred for each sample. Among the four samples, Sample A fallen first under the JMA Kobe NS wave with a time scale of 50% and amplitude of 4%. The maximum amplitude here was 16 mm. Sample B fallen under an input wave with an amplitude of 16%. All components vibrated together first, but the sample quickly fallen when it became unstable.
as the mortar between the foundation and sao fell off. The maximum amplitude here was 64 mm. Also, on observation of pieces of mortar that fell off from the fallen sample, discoloration was found in areas about 5 mm from the surface. This indicated the possibility that the interior of the mortar was not completely dry and did not provide adequate strength.

Vibration for Samples C and D were stopped at 20% amplitude without falling due to the types of waveform that could be used on the vibration table. This means that these samples possessed sufficient earthquake resistance compared to samples stacked without adhesive or ones reinforced only with mortar. This is probably because reinforced integration of individual components, especially the strong integration of the stable foundation and the sao section, which tends to be vulnerable to vibration, using cores and adhesives increased the rotation angle of falling limit.

### Table 5. Results whether each sample was fallen or not.

<table>
<thead>
<tr>
<th>Input wave</th>
<th>Compacted time</th>
<th>Amplitude</th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
<th>Sample D</th>
</tr>
</thead>
<tbody>
<tr>
<td>JMA Kobe (NS dir.)</td>
<td>50%</td>
<td>20%</td>
<td>× 5%</td>
<td>× 10%</td>
<td>× 20%</td>
<td>× 80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fallen</td>
<td>Fallen</td>
<td>Fallen</td>
<td>Not fallen</td>
</tr>
</tbody>
</table>

### 4.2. Based on three-dimensional image measurements

This section examines input waves which did not result in the falling of each sample in order to compare the movement of relative displacement. Comparisons of individual input waves are discussed below.

### Table 6. Results of maximum displacement.

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Maximum displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X direction</td>
</tr>
<tr>
<td>Amplitude 2%</td>
<td></td>
</tr>
<tr>
<td>Sample A</td>
<td>41.8</td>
</tr>
<tr>
<td>Sample B</td>
<td>4.7</td>
</tr>
<tr>
<td>Amplitude 8%</td>
<td></td>
</tr>
<tr>
<td>Sample B</td>
<td>7.8</td>
</tr>
<tr>
<td>Sample C</td>
<td>4.9</td>
</tr>
<tr>
<td>Sample D</td>
<td>9.7</td>
</tr>
</tbody>
</table>

**Figure 11.** Time series graph of relative displacement in case of amplitude: 2%.

**Figure 12.** Time series graph of relative displacement in case of amplitude: 8%.
4.2.1. *JMA Kobe NS wave: 50% time, 2% amplitude*

The relative displacements of Marker 1 on Samples A and B to which vibrations were applied using this input wave were compared. Figure 11 shows the outcomes. The application of mortar between components reduced the displacement at the top of the sample even under the same input wave.

4.2.2. *JMA Kobe NS wave: 50% time, 8% amplitude*

As in 4.2.1, Figure 12 shows a comparison of the relative displacement of Marker 1 on Samples B, C, and D to which vibrations were applied using this input wave. No large difference in the maximum displacement was observed among the samples. This indicated that as long as the mortar was intact in Sample B, the individual components vibrated as a strong unit in the same manner as samples in which cores were installed. Meanwhile, in Sample D, in which vibration absorption gel was expected to be effective, the effect of the adhesive on integrating the components was larger than the effect of the gel in absorbing vibration. This was probably because the performance of the adhesive was too great in proportion to the weight of the reduced-scale models used in this experiment.

5. Summary and future topics

Based on the overall outcomes of this study, the most important point in increasing the earthquake resistance of stone lanterns is to securely bond heavy, stable foundations and thin and unstable *sao* (posts) using cores or adhesives. This study used vibration tests with reduced-scale stone lantern models. However, outcomes obtained using reduced-scale models are subject to the law of similarity, and are affected by differences in model sizes and weights. Therefore, the use of full-scale models is desirable for accurate observations. In addition, it is necessary to conduct strength tests on bonds between components using vibration absorption gel, adhesives used together with cores, and mortar. In addition, while this experiment applied vibrations by placing samples on sand, coarse sand was lifted during repeated vibrations, and the ground became loose in comparison with actual ground conditions. This indicates the necessity of paying attention to the establishment of ground conditions such as solidifying sand with water or cement, or securing samples to bottom plates with anchor bolts.

References


Relationships between Ancient burial Mounds’ Construction Methods in Korean Peninsula and Northern Kyushu, Japan

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Abstract

Dolmens (B.C.7~B.C.8 hundred) and cairn (stone burials, B.C.1 hundred) in the North of Korean Peninsula were introduced from the cold and less rain climatic Northeastern Region, China. And burial mounds in the Le lang commandery (about B.C.1.hundred~A.D.3.hundred) were introduced from dry and the semi-dry climatic Yellow River basin. Their construction methods including burial style were affected by those in China. Le lang burial mounds are similar underground burial style to the Yellow River basin’s burials, and this construction method developed to the cairn burials with wooden compartments in Sinra (late A.D.3.hundred~). On the other hand, burial mounds (B.C.1.5 hundred~) in the warm and wet climatic Northern Kyushu, Japan followed the Jiangnan burial mounds (B.C.1.1~B.C.0.2 thousand) construction method in the lower Chang River basin because of similar climate. This is an overground burial style which is a revolutionary change from the traditional underground burial to protect burial matters from the ground water. Dolmens and burial mounds (A.D.2.hundred~) in the Southwest of Korean Peninsula are similar shape and burial style to those in Northern Kyushu, Japan. There seems to be close relations between burial styles of Korea and Japan. The construction methods including burial styles in Korean Peninsula and Northern Kyushu, Japan have been influenced by those in China and have individually developed according to their natural environments. And their construction methods affected each other between Korean Peninsula and Northern Kyushu, Japan.

Keywords: Ancient burial mounds, Construction method, Natural environment, Korean Peninsula, Japan

1. Introduction

Lots of ancient burial mounds are valuable heritages. This paper deals with construction methods of these burial mounds in the Korean Peninsula and Northern Kyushu, Japan which are separated by the Channel. The construction methods such as compaction method and burial style in both regions have been influenced by those in China and have individually developed according to their natural environments (climate, geography and geology) and era. And their construction methods affected each other between both regions. The focused time is about B.C.3 thousand to A.D.3 hundred which is the end of Yayoi period of Japan. The relationship between construction methods of both regions according to their natural environments is mentioned.

2. Cairns and dolmens in the neighboring region (Northeastern region of China) of Northern Korean Peninsula

2.1. Cairns

In the Northeastern region of China, cairn (stone mound) burials started in the late New Stone age (B.C.8~B.C.2 thousand), and dolmens and stone coffin burials followed (Higashi and Tanaka, 1995). Cairns are filled with river field stones, and human remains or coffins are set in the cairns.

These regions are mountainous and under cold and less rainfall climate. It can be easy to get river field stones from the low water level river different from the Yellow River basin. For the construction of burial soil mounds, it needs the tools and techniques for soils’ excavation, transportation and compaction, but in the case of
cairns, it is easy to construct by only human forces. The cairns are suitable burial structures for the natural environments. It is lower level’s construction method comparing with the burial mounds in the Yellow River basin where the Hanchiku method (the highest level’s compaction method, Japanese) (Onitsuka, 2012) was borne and developed.

The cairns in Niuheliang remains (Hongshan Culture period, B.C.4–B.C.3 thousand), Liaoning Province are well known as early cairn burials shown in Figure 1. The cairn burials appeared in Koguryo in B.C.1 hundred and developed to large sized burials such as the General tomb (early A.D.4 hundred) which has a corridor-style stone chamber in Jilin Province (Saotome, 2000). The burial locates on just near North Korea. It is shown in Figure 2. Except for early cairn burials, generally human remains and coffins are buried in these cairns. Hence, it can be said that the burial location is over the ground.

![Figure 1. Early cairn burials in Koguryo (Gogureo), Niuheliang remains, Liaoning Province, China (a): total view (b): stone coffin and cairns.](image)

### 2.2. Dolmens

The dolmens are found in around the world in the period from the late New Stone age to Stone-Metal Utilizing age. This is a large stone burial, where some stones on the ground support a large cap stone. Exactly speaking, the dolmen doesn’t belong to the category of the burial mounds. In considering the ancient burial mounds’ start, development and propagation, it isn’t proper to omit the description on dolmens.

The dolmens in China mostly exist in the Liangdong Peninsula and its neighborhood (Liaonin Province Archeological Institute, 1994). The construction time is about B.C.1.5~B.C.0.5 thousand. The dolmens in China are classified into two groups, namely Stone shelf and Large stone cap burial. The Stone shelf is a burial where three or four tall plate stones support a large ceiling stone. The Large stone cap burial may be named so in that the ceiling stone looks like a cap because of low supporting stones.

Figure 3 is a typical Stone shelf in the Liangdong Peninsula. It is known that dolmens exist also in Ruian, Zhejiang Province. These dolmens in Figure 4 were constructed during the West Zhou period and the Spring-Autumn period (B.C.1.1~B.C.0.5 thousand). As explained later, many Tudunmu (in Chinese, burial mounds in Jiangnan, the lower Chang River basin) were constructed there in the same period.

### 3. Dolmens in the Korean Peninsula and Northern Kyushu, Japan

#### 3.1. Dolmens in the Korean Peninsula

Dolmens from the Northeastern region of China were introduced to the Korean Peninsula about B.C.8~B.C.7 hundred. Table-type (or Northern type) dolmens appeared in the Northwest and Go-table-type (or Southern type) dolmens appeared in the South-west of the Korean Peninsula. The Table-type dolmen as shown
in Figure 5 is the same type of the Stone shelf in China. And the Go-table-type dolmen is similar to the Large stone cap burial in China, and it is called as the Southern type dolmen (Saotome, 2000). Dolmens in Ganghwa, Gochang and Hwasun are designated as the World Heritage Site. It is said that Ganghwa dolmen is Northern type, Hwasun dolmen is Southern type and Gochang dolmens are both types.

3.2. Dolmens in Northern Kyushu, Japan

In Northern Kyusyu as well, dolmens were constructed during the late Jyomon period (B.C.1 thousand) and early Yayoi period (about B.C. 3 hundred). The shape is the same as the Southern type dolmen in the Southwest of the Korean Peninsula as shown in Figure 6. The burial locations in both the Stone shelf and the Northern type dolmens are on the ground, and these in both the Large stone cap burial and Southern type dolmens are under the ground. Concerning the dolmens in Northern Kyushu, human remains are buried in the pit under the ground. There are some cases in which a burial Jar is found in the pit. There is a question that these dolmens in the Southwest of the Korean Peninsula and in the northern Kyushu, Japan originated from the Northeastern region of China, or from Zhejiang Province. The author thinks that dolmen’s construction method in Zhejiang Province propagated to the Southwest of the Korean Peninsula and northern Kyushu, through the sea. This question is a big subject concerning the origin and propagation of the dolmen in Japan.

4. Wooden compartment burials under the ground in the Korean Peninsula

4.1. Origin of wooden compartment burials: burial mounds in the Yellow River basin, China

The main burial style in the Yellow River basin is the large sized wooden compartment under the ground in the Spring and Autumn period and the Warring State period (B.C.1.1 thousand–B.C.0.2 thousand). The old wooden compartments go back to the Yin period (Fuan, 2003).

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**Figure 2.** General tomb in Jian, Jilin Province, China.

**Figure 3.** A typical Stone shelf in Shipengshan, Gaizhou, Liaoning Province, China.

**Figure 4.** Large stone cap burial in Ruian, Zhejiang Province, China.

**Figure 5.** Dolmens in the Korean Peninsula (a): Table (Northern) type (b): Go-table (Southern) type.
Early burial mounds in the Yellow River basin appeared in the end of the Spring and Autumn period (B.C.5 hundred) (Yang, 1981). And, in the Warring State period, large sized burial mounds such as the Mausoleim (big burial mound) of the First Qin Emperor appeared. However burial matters including underground palace of all burial mounds are set under the ground not in the fill. The underground burial style relates to the dry and semi-dry climate and deep water table in the Yellow River basin.

4.2. Lelang burial mounds group with compartment

After setting of the Lelang Commandery (B.C.108 ~A.D.313) in the West Han period, lots of burial mounds were constructed near in Pyongyang at present. These are called as “Lelang burial mounds group” which has wooden or brick compartments under the ground. These burial style and compaction method were introduced from these in the Yellow River basin where the ground water level is deep. The shape is square or rectangular, and these are 15~30m in length and 2~5m in height. The depth from the ground surface to the bottom of the compartment is 3~6m (Shuppankagakusogokenkyusho, 1981). One of the Lelang burial mounds is shown in Figure 7.

Figure 6. Dolmens in Northern Kyushu, Japan (Maruyama remains, Saga).

Figure 7. Lelang burial mounds.

4.3. Sinra cairns with compartment

In Sinra of the Three Kingdoms of Korea period (late A.D.3 hundred~), many cairns with wooden compartment were constructed. These burials install a wooden compartment under the ground and fill stones on the ground, and finally cover around cairns (stone fills) with soils. Except of the Heaven horse tomb (Kyongju, early A.D.6 hundred) in Figure 8 (Korean Administration of Culture Publicity and Cultural Properties 1975), most of burial mounds in Kyongju have their wooden compartment under the ground. Like this, burial mounds which follow those in the Yellow River basin have a characteristic such as installing their compartment under the ground.

5. Burial mounds in Northern Kyushu, Japan and in the Korean Peninsula

5.1. Origin of over ground burial: burial mounds in Jiangnan, lower Chang River basin

The burial mounds (Tudunmu in Chinese) in Jiangnan, the lower Chang River basin have been constructed during the Western Zhou period and the Warring State period (B.C.1.1 thousand~B.C.2hundred). As shown in Figure 8, human remains are set on the ground in the earth fill. The diameter is 6 to 40m, the height is 2 to 7m as shown in Figure 9. Generally normal sized burial mounds are compacted using almost same soil by the Sochiku
method (second level’s compaction method defined by Onitsuka, 2002, 2003, 2008, 2012, 2012, Japanese). The large sized burial mound for aristocrats was compacted politely to horizontal layers using different soils. Each soil layers were constructed inorder to mobilize their function. The compacted method can be Sochiku or Hanchiku (Onitsuka, 2012).

This is a revolutionary change on the burial style from the burial pit under the ground to the burial mound over the ground. The reason of change from underground burial to overground burial is needless to say to protect the burial matters from damage by the underground water and seepage water. The burial mounds sizes in the Warring State period became larger for burials of aristocrats and kings. Some of them were constructed by the Hanchiku method and seepage water controls became more elaborate.

The author considers that Jiangnan’s burial mound is the root of Yoshinogari burial mound (about B.C.1.5 hundred) as shown later. Namely the construction technique of Jiangnan’s burial mound propagated to the Shandon Peninsula, and these construction techniques of Jiangnan’s or Shandon Peninsula’s burial mounds propagated to Yoshinogari in Northern Kyusyu, Japan through the sea, not through the Korean Peninsula (Onitsuka et al., 2011).

Figure 8. A vertical cross section of Heaven horse tomb with a wooden compartment, Gyeongiu, Korea.

Figure 9. Schematic figure of burial mound in Jiangnan, China.

Figure 10. A normal sized burial mound in Jiangnan, China.
5.2. Burial mounds over the ground in Japan

The oldest and large Yoshinogari burial mound in Japan was constructed at the highest location of the hill by Sochiku compaction and Taichiku compaction (the lowest level’s compaction method, Japanese) (Onitsuka, 2012). After that, burial jars were laid on the dug hole and back filled very densely as shown in Figure 11. The higher natural water content soil than the optimum water content can be compacted by foot. The overground burial is similar to the Jiangnan burial style. The ancient people in Northern Kyushu employed Jiangnan style because of similar environments. However, they utilized large sized jars instead of traditional coffins or compartments. This is a new idea to protect burial matters from damages due to the ground water.

All burial mounds in Japan which followed the Yoshinogari burial mound are the overground burials which are similar to Jiangnan burials. And later Japanese burial mounds with a stone room (Kofun in Japanese, A.D.3 hundred to 7 hundred) have burial matters in the stone room. It is also the overground burial style.

Figure 11. Yoshinogari burial mound (a): total view (b): burial jar (c): soil layer by sochiku method.

Figure 12. Burial mounds in the Korean Peninsula and Northern Kyushu, Japan.
5.3. Burial mounds in the South of Korean Peninsula

It seems that Yeogsan River basin in the South-west of the Korean Peninsula (South Jeolla Province), jar burials with a mound were constructed in A.D.2 hundred (Saotome, 2000; Pak, 2001). The burial jars became larger in size in A.D.4 hundred and burial mattes became gorgeous (Saotome, 2000). Both in the basin of Geum River which flow through Buyeo, ancient Paekche (Baekje)’s capital, and Yeungnam region, (Gyeonsang Province), Sinra and Caya ancient country existed, human remains and burial matters were installed under the ground, then a mound was filled. Namely, this is an underground burial style or the burial mound construction is a postdated style.

On the other hand, in the Yeogsan River basin and the lower Geum River basin, the human remains and burial matters were installed in the filled burial mound. This is an overground burial style or burial mound construction is an antecedent style. As shown above, the burial mound style in the Southwest region of the Korean Peninsula is similar to Yoshinogari remains and other remains in Northern Kyushu. And similar style dolmens were constructed in both regions, hence it can be said that the Southwestern region of the Korean Peninsula and the Northern Kyushu have a common burial system.

The burial style of horizontal stone chamber in the Korean Peninsula was introduced from China through the Lelang district in A.D.4 hundred. This may have propagated to Paekche and Sinra in A.D.6~7 hundred. Especially in the Yeogsan River basin, many burial mounds which resembles to Keyhole-shaped burial mound in Japan concentrated (Saotome, 2000; Pak, 2001). The most of them have a horizontal chamber and the burial location is over the ground such as burial mounds in Japan. There seems to be close relations between burial systems of Korea and Japan.

6. Conclusions

Dolmens (stone shelf, about B.C.8~7 hundred) and cairn burials (about B.C.1 hundred) of the Northeastern region of China were introduced to Northern Korean Peninsula. Table type dolmens (or Northern type) as same as Stone shelf in China appeared in the Northwest of the Korean Peninsula and Go-table-type(or Southern type) appeared in the Southwest. Also in Northern Kyushu, Japan, similar dolmens as the Northwest of the Peninsula were constructed. There is a question that these dolmens in the Southwest of the Korean Peninsula and in the northern Kyushu, Japan originated from the Northeastern region of China, or from Zhejiang Province.

The Lelang burial mounds group and followed Sinra cairns with wooden compartment have their compartment under the ground. These burial mounds were propagated from the Yellow River basins’ burial style under dry and semi-dry climate which installs coffins and compartments under the ground.

The oldest and large Yoshinogari burial mound (B.C.1.5 hundred, Jar burial) and followed burial mounds in Japan was constructed on the ground, and after that burial matters were laid on the dug hole. These are overground burials. Ancient people employed Jiangnan burial style, namely overground burial style, because Northern Kyushu climate is similar to that of Jiangnan. The overground burial style is revolutionary change from traditional underground burial style and ancient people’s excellent idea.

Burial mounds in the Southwest of the Korean peninsula are similar to Jar burials in Kyushu, Japan, namely overground burials. And Dolmens in both regions are same type. In addition, burial mounds similar to Japanese Keyhole-shaped burial mounds concentrated in the Southwest of the Korean Peninsula. There seems to be close relations between burial style of Korea and Japan.

References

Study on Preservation Methods of Imperial Citadel of Thang Long Based on Heat and Moisture Movement in the Remains

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Abstract

Imperial Citadel of Thang Long located in Hanoi consists of several remains belonged to successive dynasties from 11th to 19th century and central sector of imperial citadel was listed in UNESCO’s World Heritage Site in 2010. Since these remains have been openly exhibited, these soil site remains were deteriorated due to drying and salt precipitation. In this study, to consider deterioration mentioned above, which is derived from heat and moisture movement, some soil tests about thermal and hydraulic properties and field survey were conducted. In the field survey, meteorological observation had been conducted from 2009 and both water content and water potential in the soil were measured. Moreover, to consider preservation method by covering the remains with sandy soil, water content and water potential were also measured while covering the surface with sandy soil. Based on the results of soil tests and field survey, numerical analysis on coupled heat and moisture transfer in the soil site were performed to evaluate the effectiveness of reburying method. As a result of both observation and numerical analysis, it was suggested that water content of original surface of the remains could maintain high if covered with sandy soil. Hence, we may conclude that it is effective to cover the surface with sandy soil to preserve the remains.

Keywords: Thang Long, Soil site, Simultaneous heat and moisture transfer, Water potential, Numerical analysis

1. Introduction

In case soil site is openly exhibited, generally the covering roof, as a protection facility, is installed to reduce negative impacts of insolation, wind and rain. Under such circumstances, on the surface of the remains there is predominantly upward moisture movement in the vertical direction. Thus, in the environment of sluggish water supply, the drying on the surface of the site is progressing and the deterioration of the remains occurs, such as cracking and losing plasticity of the soil, which in turn results in collapse. Under the circumstance that relatively sufficient moisture is supplied, the salts dissolved in the soil water precipitates near the surface of the remains, which destroys the surface of the remains. Accordingly, in the preservation of soil site, examination on moisture movement in the site is quite important. In this study, we conducted field survey on heat and moisture movement around Imperial Citadel of Thang Long.

Furthermore, one of the best methods to preserve the soil site is reburying the original surface of site with soil. In order to verify how the condition of the reburied remains actually is and to examine how effective the reburying method is, water content and water potential in the soil were measured at 2 areas. One is openly exhibited area and the other is reburied with sandy soil. A simulation analysis was also conducted using meteorological data and physical properties of the soil at the site and examined the moisture movement in both two cases, when the remains were buried with sandy soil and when the remains left unburied.

2. Methods on field survey and numerical analysis

2.1. Field survey

In the section D at the Thang Long site (expressed as Section D in the following), where the site is openly

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exhibited under the simple covering roof, it can be guessed that the north side and South side have different groundwater levels. Hence, observation points were set at both north (point 1) and south side (point 2) as shown in Figure 1. Regarding the point1, water potential and water content were observed since December 2010 at each depth of 20cm, 40cm, 60cm, 80cm and 100cm from the surface level of the site. At point 2, at each point of the same depth above-mentioned, water contents were measured since May 2010. At the point 3, both water content and water potential were measured at the depth of 20cm, 40cm, 60cm and 80cm from the surface level of the site. Then the site was covered with about 20cm layer of sandy soil, and also water potential was measured in the sandy soil at the depth of 10cm. This measurement was continued until August 2013. The measurement range of the matric potential sensors used was from -10 to -500 kPa.

Figure 1. Observation points at the section D, No.18 Hoang Dieu.

2.2. Soil tests

2.2.1. Soil samples

An undisturbed sample of the soil of the remains collected in Section D was used for soil testing, in which thermal conductivity and unsaturated hydraulic property were measured. To collect the sample, a 100cc cylindrical specimen container was used. To the collected undisturbed sample, water was supplied from below through Mariotte’s tank, and it was left for three days for water saturation treatment. Then it was dipped in water being and in a decompressed condition for a twenty-four hour period, which marked the end of water saturation treatment, and it was used as the specimen for the experiments stated below.

2.2.2. Thermal conductivity

To measure the thermal conductivity, a 3cm-long sensor was used. This sensor was inserted in a 5.1cm-long specimen that had had water saturation treatment and its thermal conductivity at the saturated condition was measured. Since thermal conductivity changes by soil particles and water content, it will be a function of water contents. Thus it is desirable to measure thermal conductivity at several water contents. However, when water content was low, vapor movement following latent heat transfer occurred and the measured values of thermal conductivity may include a large error. Thus, in this experiment the thermal conductivity was observed both in a water-saturated condition and an absolute dry condition. It was assumed that thermal conductivity would change in a linear manner according to the water content.

2.2.3. Water retention curve and unsaturated hydraulic conductivity

Regarding the unsaturated hydraulic property of the soil, van Genuchten-Mualem model was adopted (van Genuchten, 1980; Mualem, 1976). This model indicates the relationships between water potential and volumetric water content and the relationships between (liquid phase) hydraulic conductivity and volumetric water contents with fitting parameters (Table 1). An evaporation method and a saturated salt solution method
particularly for a drying region were performed so that the constant term and the values of fitting parameters in the model were estimated by an inverse analysis (Šimůnek et al., 1998). The salt used in the saturated salt solution method is shown in Table 2.

Table 1. van Genuchten-Mualem model.

| Water contents |  
|----------------|----------------------|
|               | \((\psi) = \left(\frac{1}{\psi_{sat}}\right)^\gamma \left[\frac{1}{g}\right]^\frac{\gamma}{\beta} + \frac{\gamma}{\beta}\) |
| Hydraulic conductivity | \(\sigma = K_{sat} \frac{\mu}{g} S_e \left[1 - \left(\frac{\psi_{sat} - \psi_r}{\psi_{sat} - \psi_{r 0}}\right)^n\right]^{m/2}\) |

\(\psi\) : Volumetric water content [m³/m³], \(\psi_{sat}\) : Saturated volumetric water content [m³/m³], \(\psi_r\) : Residual volumetric water content [m³/m³], \(\alpha, n, m=1-1/n\) : fitting parameter, Units are respectively [m⁻¹], [-], [-], \(\mu\) : Water Potential [J/kg], \(g\) : Gravitational Acceleration (=9.8) [m/s²], \(\lambda/\mu\) : Liquid phase water conductivity of a water potential gradient [kg/[m s J/kg]]], \(K_{sat}\) : Liquid phase water conductivity in a saturated state [m/s], \(\rho_w\) : Density of water (=1000) [kg/m³], \(S_e\) : Effective water content \((\sigma(\psi-\psi_r)/(\psi_{sat} - \psi_r) [-]\)

The equations shown are modified from the original to adapt the unit.

Table 2. Saturated salt solution methods.

<table>
<thead>
<tr>
<th>Salt</th>
<th>RH [-]</th>
<th>Water Potential [J/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>KNO₃</td>
<td>0.95</td>
<td>-6940</td>
</tr>
<tr>
<td>KCl</td>
<td>0.85</td>
<td>-21900</td>
</tr>
<tr>
<td>NaCl</td>
<td>0.75</td>
<td>-39000</td>
</tr>
<tr>
<td>NaBr</td>
<td>0.59</td>
<td>-71100</td>
</tr>
<tr>
<td>MgCl₂ · 6H₂O</td>
<td>0.33</td>
<td>-148000</td>
</tr>
</tbody>
</table>

2.3. Numerical analysis

The numerical analyses were performed to estimate the changes of temperature, water contents and water potential in the soil with the observed meteorological data and to evaluate the effectiveness of covering the site with sandy soils. The fundamental equation used here is the simultaneous heat and moisture transfer in porous material, as shown in Table 3. As for the heat balance of the ground surface boundary, the heat transfer between air and the surface soil, solar radiation, nocturnal radiation and the heat conduction by latent heat and subsoil were considered. Regarding moisture, moisture transfer between the air and soil and moisture conduction to subsoil was considered. The meteorological data sets were repeatedly applied to calculate for fifteen years, which means five cycles of the data of three years, to obtain a periodic steady state, which was considered as the analysis result. Since there is no information on groundwater level, it was supposed to be constant at 1 m deep from the surface of the site. The soil temperature at 5 m deep from the surface was supposed to be steadily 17.0°C, which is the average of yearly temperature. Although its details are not mentioned here, the nocturnal radiation was calculated based on Brunt formula, which was then adjusted to the degree of cloudiness. Table 4 shows the constant terms used for the analysis.

3. Results and discussion

3.1. Field survey

The daily precipitations in 2012 are shown in Figure 2 and water potential observed at Point 1 during same period is shown in Figure 3. As shown in Figure 3, the water potential increased rapidly at the beginning of rainy season. On the 1st June at each depth of 100cm, 80cm and 60cm, the values are -14kPa, -16kPa and -14kPa, which correspond to nearly saturation. Particularly focusing on May 2012, Figure 4 shows the change of water potential for a month from 16th May to 15th June. It indicates that water flows from the bottom then gradually moves upwards, as water potential increases gradually from 100cm, 80cm, 60cm, 40cm to 20cm as can be seen from this graph. Furthermore since the water content of the surface soil was almost saturated by the end of the
rainy season, the surface of the remains could be deteriorated by the precipitation of salts.

Results of field survey of both openly exhibited area (Point1) and reburied area (Point3) observed from August 2012 to August 2013 were compared. Figure 5 shows water potential observed at Point 1. As shown in Figure 5, water potential decreased from the depth of 20 cm to of 100 cm in turns during the period of dry season. It corresponds to the fact that drying of the soil develops gradually from the surface. Figure 6 shows the water potential observed at Point 3. During the period of dry season, water potential in sandy soil layers decreased drastically, which means that drying was in progress, while change of potential in the soil of remains could hardly be seen at the depth of 20 cm, 40 cm, 60 cm, and 80 cm. This indicates that there was only very little moisture movement within the remains, which can be attributed to the method of reburying remains with sandy soil that could control the amount of water lost through evaporation from the remains surface.

3.2. Soil tests and Numerical analysis

The thermal conductivity of the soil obtained from the remains is shown in Figure 7, and the water retention curve that represents the relationship between water potential and volumetric water content is shown in Figure 8. Figure 9 shows the calculated variation of absolute value of water potential at near the surface of soil for three years under the condition of that the surface were exposed as a single layer model. As shown in Figure 9, it is suggested that at the depth of 10 cm and deeper the soil water contents barely changed and constantly maintained a high water-content state. On the other hand, on the surface of the remains (d=0.0 m) and at the depth of 3 cm changes in water potential were estimated between January and April each year, influenced by the external meteorological conditions, so that the water contents decreased to 0.05 m$^3$/m$^3$. As mentioned above, while on the surface the water potential fluctuated in the range of a very low value (therefore, in the range of a very high value in the Figure 9 because it is expressed in absolute value), at the depth of 10 cm and deeper, water potential scarcely changed and particularly at the depth of 21 cm it shows the nearly saturated. From the above results, it is suggested that, when the remains are exposed under the condition of groundwater level constantly staying at GL-1 m, at the depth of 10 cm and deeper the water contents could generally be kept at a high state, but on the surface layer the water contents showed a sudden decrease, which resulted in the soil losing plasticity and deterioration.

### Table 3. Foundational equation of heat and moisture transfer.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(c\rho)_{ap} \frac{\partial T}{\partial t} = \nabla \cdot \left[ \left( \lambda + r \lambda' \right) \nabla T + r \lambda' \gamma \nabla \mu \right]$</td>
<td>Heat balance</td>
</tr>
<tr>
<td>$\rho_w \frac{\partial \psi}{\partial t} = \nabla \cdot \left[ \lambda'<em>{\mu} \left( \nabla \mu - gn \right) + \lambda'</em>{\mu} \nabla T \right]$</td>
<td>Moisture balance</td>
</tr>
<tr>
<td>$(+r_s)(T_b, T_s) + r \left( \frac{T}{y} \right) + Q_{solar} + Q_{noc} = - l + r \left( \frac{T}{y} \right)$</td>
<td>Heat flow on the surface of soil</td>
</tr>
<tr>
<td>$(b \sigma s + r \left( T_b, T_s \right) = - y gn \frac{T}{y}$</td>
<td>Moisture transfer on the surface of soil</td>
</tr>
</tbody>
</table>

*(cρ)*$_{ap}$: Apparent heat capacity of material [J/(kg · K)], $n$: Perpendicular downward vector [-], $Q_{noc}$: Nocturnal radiation [W/m$^2$], $Q_{solar}$: Solar radiation [W/m$^2$], $r$: Latent heat [J/kg], $T_b$: Temperature [K], $T_s$: Outdoor temperature [K], $\alpha_{\mu}$: Moisture transmissibility related to water potential gradient [kg/(m$^3$·s·J/kg)], $\lambda':$ Thermal conductivity in the soil of the remains [W/(m·K)], $\lambda':$ Moisture conductivity related to temperature gradient [kg/(m$^3$·s·K)], $\lambda'_{\mu}$: Moisture transmissibility related to water potential gradient [kg/(m$^3$ · J/kg)], $\lambda':$ Moisture conductivity related to temperature gradient [kg/(m$^3$·s·K)], $\lambda':$ Vapor phase moisture conductivity related to temperature gradient [kg/(m$^3$·s·J/kg)], $\lambda'_{\mu}$: Vapor phase moisture conductivity related to water potential gradient [kg/(m$^3$·s·J/kg)], $\mu$: Water potential of vapor in outside air [J/kg], $\mu$: Water potential of moisture in the soil of the remains [J/kg]

### Table 4. Constant value in the analysis (Li, 2010).

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer coefficient (outside)</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>Moisture transfer coefficient (outside)</td>
<td>$\alpha'$</td>
</tr>
</tbody>
</table>
Figure 10 shows the variations in water potential when the surface of the remains was reburied with 20cm thick sandy soil as a double-layered model. Figure 10 shows the water potentials at three points, namely at the surface and the depth of 3 cm of the sandy soil covering the remains, and at the depth of 21 cm from the sandy soil surface, where corresponds to the depth of 1 cm of the original surface of the remains. Figure 10 shows that the water potential in sandy soil showed changes between January and April every year, while during the other periods it remained at very low values (therefore, they appeared high due to the indication method in absolute values). On the other hand, at the original surface of the remains the value was always kept at around -10 J/kg, which corresponds to saturated state. Because the sandy soil is poor in water retentivity, water content of it decreased easily. Therefore, it is suggested that the hydraulic conductivity of sandy soil also significantly decreased, which led to an extremely sluggish water movement upward from the original surface of the remains. From the above results, we may conclude that, by reburying the remains with sandy soil, the original surface of the remains can be kept in a high water-content state, and degradation due to decrease in water-retaining condition, such as cracks, can be restrained. At Thang Long site, white salts precipitated mainly on bricks, in some parts the surface of bricks detached. The treatment for salt crystallization requires further study. The origin of salt, which might cause deterioration of bricks, is ions dissolved in soil water. Since the water potential, which salts can precipitate, differs from the kinds of salt, a point (or depth in vertical one-dimensional model), where a salt precipitates, varies according to the kinds of salt. However, it can be considered that the more water evaporates, the more salt generally deposit. Therefore, the risk of deterioration caused by salt will be examined here, in reference to the changes in amount of evaporation according to whether the remains are buried with sandy soil or not.

Figure 11 shows the amount of evaporation at each soil boundary in the 2 models mentioned above; on the surface of the remains in a single layer model (noted as “Sites soil surface (1 Layer)” in Figure 11) and on the surface of the sandy soil and on the original surface of the remains in a double layer model (noted as “Sandy soil surface (2 Layers)” and “Sites soil surface (2 Layers)” in Figure 11 respectively).
The latter two were calculated results when the remains were buried with sandy soil as a double layer model. The amounts of evaporation are shown with negative value, hence the larger absolute value represent the larger amount of evaporation. The results shown in Figure 11 suggest that when the original surface of the remains was openly exhibited, the larger amounts of water evaporated on the surface compared to the one buried with sandy soil. It is suggested that, due to the relatively high water retentivity of original soil, decrease of water content was sluggish and therefore hydraulic conductivity was tend to be kept high. On the other hands, when the remains were buried with sandy soil, the amount of evaporation from the original surface of the remains was very little. Thus, it is found that, by reburying the remains with sandy soil, the deterioration due to salt precipitation can be largely restrained.

4. Conclusions

In order to examine the preservation method for Imperial Citadel of Thang long, local weathering observation, field survey on moisture movement and numerical analysis on moisture movement in the remains based on the physical properties obtained from soil tests. Field survey was carried out at north and south points in the section D, where noted as Point 1 and Point 2 respectively. Furthermore, small area noted as Point 3 close to Point 1 was reburied with sandy soil, and then water content and water potential were also measured. As a result, it is found that water content at Point 1 increased rapidly in rainy season and even near the surface soil maintained almost saturated condition for a while. Hence, it is suggested that the remains might be deteriorated due to salt precipitation. At Point 2, before 2012 the water content scarcely varied, but it showed drastic change during rainy season in 2012.
Since water content of the surface soil showed relatively low in most period of a year, there is a risk of collapse due to drying. In the examination on reburying method, we gained similar results from both observation conducted at Point 3 and numerical analysis. It is found that, by reburying the remains with sandy soil, the water content of the original surface of the remains can be kept high, through whole a year and amount of evaporation at the original surface can be reduced. Therefore, deterioration due to decrease in water-retaining condition, such as cracks and salt precipitation can be restrained and we may conclude that reburying method is quite effective on the preservation of soil site remains.

Acknowledgements

We would like to express our gratitude to Dr. Bui Minh Tri, head of Centre for Imperial City Research for his permission to obtain the soil samples from the remains. The soil samples were imported with special permission for import from the Ministry of Agriculture, Forestry and Fisheries.

References

Recuperation of the Traditional Construction in Contemporary Interventions in Oaxaca, Mexico

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Abstract

The state of Oaxaca, located in southern Mexico, has an ancestral earth traditional construction, derived from the fusion of Pre-Hispanic civilizations with the Spanish tradition. A part of these traditions have remained due to its vernacular application. Today, as a consequence of the rural migration to the cities, the economy, values and knowledge of rural communities have been changing. They tend to be deceived by the new models imported from the exterior, totally unadapted and decontextualized to the climate or rural landscape of Oaxaca. As a result, an important heritage is being forgotten. The vernacular houses are abandoned, leading to a fixed idea that these structures are unsafe, unhealthy and associated with poorness. The substitution of the natural materials for the industrial ones results in innumerous problems. At first, earth and stone structures have been progressively abandoned or destroyed to construct new but unadapted buildings; on the other hand, new interventions (constructions and reconstructions in vernacular heritage) are done with incompatible materials, causing serious structural problems that conduces to a faster degradation, increasing the lack of trust in these materials. So, in the last decade it has been made an effort with several initiatives to recover the traditional construction, applying local technology improvements with an ecological vision. The aim of this article is to show three good interventions, where new technological improvements were used without disrespecting the nature of the materials. The reconstruction of Casa Allende, made of earth and the Cacica, made of stone, shows the respect for the preexistence but also for the new and actual needs of its users; on the other hand, the construction of the Sports City, an emblematic and urban building, shows the timeliness of natural materials and its possibilities to be used with the ultimate high technologies. Initiatives that have been leading to the revitalization of the vernacular techniques in Oaxaca.

Keywords: Revitalization of vernacular techniques, Earth and stone, Appropriate and sustainable interventions, Learning from heritage

1. Introduction

A large number of stone and earth buildings can be seen in a vast range of the territory in Mexico. The correct use of local materials like earth, stone, wood or bamboo have allowed the construction of all kind of buildings for thousands of years, from small shelters to big scale constructions. Despite its durability and resistance, these materials have been progressively replaced by the industrial ones, easy to achieve, but non adapted to the local climate, cultural and social characteristics. The use of these “modern” materials is even more concerning in areas with low resources, where the practice of traditional techniques has allowed some kind of subsistence and the development of the communities. This change of paradigm leads to a possible loss of knowledge of the traditional building techniques that are in risk of being irreversibly forgotten. Consequently, the old structures are seen with no interest and left without maintenance, provoking its failure and consequently the devaluation of these materials. It is also important to notice the negative impact of the medias and the politics supported by economical interests and construction lobbies (Caeiro, 2013b).
The problematic is imminent and, for that reason, in the last decade it has been made an effort with several recuperation initiatives of the traditional earth and stone construction, applying technological improvements with an ecological vision. The developed projects in Oaxaca prove the capacity of creation of social engineering, in experiments that conjugates the practice work with the academic theory, considering the manual labor, usually forgotten in our formation, a vital element to the understanding of a material or a technique. The intention is to find forms of construction more adapted to the modern reality and to raise some questions about the actual tendency of intervention, totally decontextualized with its insertion and without any respect for the traditional methods of construction.

2. The context of Oaxaca

The state of Oaxaca, located in southern Mexico, has an ancestral constructive tradition in earth and stone (Figure 1 and Figure 2) that can be observed even today in innumerable buildings, both in urban and rural world. A large part of that constructive tradition has remained due to his vernacular application, mainly in isolated communities, where the self construction is still a common practice. The use of natural materials allied with the traditional techniques allowed the construction of churches, temples, houses and schools. Spaces that are totally adapted to the bioclimatic conditions of the region, respecting the climate, the culture, and in the case of Oaxaca, the structural security needed in such a seismic zone. It has been used techniques like adobe, “bahareque”, red brick, rammed earth and “blá” or “muro a la negra”, a Zapoteca’s traditional constructive technique. The adobe is still the most common technique. The junco was also used to build roofs, walls, and bamboo in storehouse and little structures in the coastal zone. These techniques are a result of the fusion of Pre-Hispanic civilizations with the Spanish tradition imposed after the colonization in the no 16th century (Baca, 1994).

3. Current situation

The common use of industrial materials, instead of the traditional ones, leads to a strong rejection of its use. There is a lack of trust on the vernacular constructions as they tend to be seen as insecure, unhealthy and just adapted to people with low resources (Forjaz, 1999). An idea that just derives from the ignorance of the most citizens and the fact that there is no interest in its disclosure – the natural materials do not create money as the industrial ones.

The loss of knowledge has a big impact on both social and constructive culture:
- Communities have to buy prefabricated products, instead of buying local manufactured things, putting in risk its own tradition and economy, decreasing the chances of the rural world. Everything needs to be
bought and the local economy fails - the money generated goes to the large cities impoverishing ruralities and enriching urbanites. Considering the construction of a house is the biggest investment of a family, the choices they make on the materials can really help them to improve their quality of life (Caeiro, 2013b).

- A combination of the lack of resources and knowledge of the inhabitants leads to low quality constructions, where incompatible techniques and materials are mixed with no criteria, creating insecure constructions that only increases the prejudice on the natural materials (Baca, 2006; 2007). It is really common the use of cement plasters that do not allow the natural breathing of walls, leading to the accumulation of humidity in its interior and consequent deterioration, provoking its failure (Rodrigues, 2004). Another current mistake is the introduction of vertical concrete structures in earth buildings that cuts the connections between the load bearing walls, separating the main structural system from the interior walls (Baca, 2013). The prejudice leads to the abandonment of the old structures and consequently its degradation and loss of patrimony (Baca, 2006; 2007). On the other hand, the new modern buildings are designed with no relation to its context, creating unadapted buildings worsening the quality of citizens’ lives.

4. Contemporary interventions in Oaxaca

In the last years it has been done an effort on the revitalization of the traditional techniques both in reconstruction or new interventions. Without denying the new possibilities, it have been introduced some technological improvements that provides better responses to the actual needs and/or requirements. One important fact is to take into account the possible influence and change that the overuse or bad use of these systems can implicate in the culture and local society, both in rural and urban world.

The protection of the heritage should be open to new possibilities, instead of being blocked in a melancholy of the past, repeating the same mistake committed by fixed truths created with the industrialization. In this time of post-industrial revolution, is urgent to make questions, to reflect in what we can learn from each world, to look for common points and develop new paradigms.

4.1. Casa Allende - renovation and restoration project of a sixteenth century building

The intervention in historic buildings involves not only the respect of the past of the building, but also the incorporation of the new local and social characteristics, dynamics, needs and values (Design by Rootstudio). Casa Allende consists in a reconstruction of an historic and catalogued building from the XVI century, located in the city center of Oaxaca (Figure 3). The building was found in bad condition, with several kinds of damage in the walls and floors, some of them resulting from bad interventions done in the XX century that attempted to its integrity and historic value. For example: the metallic sheet roof was supported by a metallic structure filled in the adobe walls with mixture of cement; it was observed several infiltrations not only in the adobe walls, but also in the adobe Catalan vault; the old and damaged lime plasters had been substituted by cement base mortar fixed with a metal net, that does not allow the natural breathing of the wall. All these interventions leaded to different typical pathologies (Achenza, 2006).

Between all the recovery works, the adobe walls were the first elements to be consolidated. The plasters were removed to analyze the kind of damage induced by the humidity (canalization and cement mixtures that didn’t allow the natural movement of the water); all the vertical concrete elements were removed and substituted by horizontal elements/reinforcements; the walls were consolidated with red bricks, a total compatible material that allows the breathing of the adobe walls; they were leveled and in one case some adobes were replaced with new ones made from the same old earth mixed with fiber. It is important to notice the infinite capacity of the earth to be recycled, so to produce the new adobes it was used the same earth but mixed with fiber that adds some reinforcement to the mixture (straw and donkey dung, traditional stabilizers used in the region). The adobes were applied with lime and sand in a 1/5 proportion. All the walls were later plastered with lime and sand in a proportion of 1/3, finished with lime paint.
In the terrace, the exposed adobe walls were superiorly covered with red bricks to protect them from the erosion (water, humans use) and to achieve at the same time a Oaxaca’s esthetic, where the red color connects all the elements: walls, tiles, metal and wood. All the metallic roofs were substituted by Oaxaca’s traditional ones made of wood structure and tiles. On the wood beams, it was collocated a wooden and/or a redbrick layer, that performed as a lost framework for the 5cm compression layer, and as thermal and acoustic insulation. Red tiles were sometimes substituted by the yellow ones, because they have less weight and bigger resistance then the red ones. In addition, all the floors were finished with handcraft elements, recovering a tradition of the historic center of Oaxaca. It is important to notice that all the water canes and electric installation were replaced and introduced in the floor to avoid future infiltrations.

The “V” wooden vertical structure supports the long roofs, allowing a better seismic behavior with a different appearance (Figure 4). These oblique columns were elevated from the floor with a metal slab (fixed through metal bolts) that avoids the rise of the humidity and the consequent wood degradation. These contemporary details give the building a modern appearance without losing its own basic principles of protection and security.

It is interesting to note out the intervention done in the first building, the one that defines the exterior façade in the main street. One of the requirements of this intervention was its reversibility, one of the most important issues in historical reconstructions (Sanna, 2011). So, in order to respond to the new owner’s needs to enlarge the space, it was built a gable roof that permitted three important issues: the reduction of the height in the exterior facade, the thickness of the wooden beams that supports the roof and consequently the overload on the adobe walls because the height it is divided in both directions. It was constructed an horizontal concrete beam, on the load bearing adobe walls, that permitted an adequate distribution of the forces from the roof to the walls (without any mechanical connection to make it reversible) and also creates a top connection of the adobe walls, improving the seismic behavior of the whole building. On the top part of the new walls it was also introduced a wooden beam that distribute the forces and make the transition between the two materials. The transition between the old and the new structure is interiorly signed with a simple and elegant red brick line (Figure 6).

The project provided a water recuperation system and a solar heating of the sanitary water. In fact, the introduction of a gable roof allowed conducting the water to a cistern located in the courtyard and the introduction of a solar panel, with the correct angle and south orientation. The spaces are naturally ventilated through small openings, only protected with a fine meshed net (to avoid insects from entering), so the indoor temperature can be adequate without the use of mechanical systems. These passive systems provide more independence of the inhabitants from the fossil energies, a very important issue in actuality.
The remodeling of Allende’s House represents a good example of an intervention on historical adobe building, with respect for its materials and its historic value, preserving the ancestral knowledge and at the same time incorporating contemporary sustainable design solutions. The whole intervention uses traditional construction techniques and vernacular values, adjusted to the reality of the XXI century. It has been achieved the respect for its preexistence, for its past and new necessities, where the village, the tradition, the handcraft, and the culture are merged with architecture and restoration. An alternative design to the actual interventions in the historical center.

4.2. Cacica – Stone Children’s library in San Pedro Teposcolula, Mixteca, Oaxaca

The Cacica archeological site had been recently converted in a children’s’ library for the local community (Project by Fundación Harp Helú Oaxaca, Design by Rootstudio & Arquitectos Artesanos). The need of more facilities as toilets and space to stock books and furniture, lead to the construction of a little storehouse and a dry toilet, a hundred meters from the historical building (Figure 6).

To respect the site, with its colors, materials and appearance, was chosen to build a 40cm stone load bearing wall, erected with the local traditional techniques, using lime and sand mortar. A simple wooden structure relays on a reinforced concrete beam that connects superiorly the four stone walls, giving a safer and seismic-resistant behavior to the whole building (Figure 7).

The roof is made of traditional handmade tiles, also used in the little opening designed for the natural ventilation of the storehouse, taking inspiration from a vernacular detail that can be found in the Oaxaca region. These openings are situated in the triangle shaped wall, that lies on the top of the stone wall in the front and the back facade. It was built with 25cm redbrick and plastered with a lime and sand mortar, to allow the wall respiration. This change of thickness (from 40 to 25cm) was solved through a single line of tiles that separates the two parts of the wall and protects from the rain the bottom part, including the entrance that lies under it.

The surrounding environment, for many years abandoned and degraded, was arranged by joining together all the rocks dispersed on the field, following the peasant’s tradition (Figure 8), used to prepare the earth before cultivation. In this case, instead of making up little drywalls on the perimeter of the field, as we can find in different parts of the world, were created circular sculptures that leave the terrain free to be used by children games and open air activities, and at the same time represent a land art reversible intervention (Figure 9).

The Sport Center belongs to a set of Mexican gymnasium, were the owners decided to risk a new approach to their line of buildings, approaching more to modern ecological trends. This 5000m2 building represents a good example of earth construction, where the nature materials are respected without denying the possibilities of the contemporary materials and technologies - a fusions between low and high tech. Earth, stone, wood, bamboo, tiles, red bricks, lime, concrete, steel and metal sheet, are combined in an harmonic way that respects the potential, the limits and quality of each material (Design by Rootstudio & Arquitectos Artesanos). All the details of the building were designed with this logic.
4.3. Sport City Oaxaca – New contemporary construction

The walls of the main building are constructed in adobe: 33 000 adobes in coffee color, elaborated with earth from the zone, mixed with horse dung, sawdust and black clay, left maturing for three days to raise the quality of the mixture. The adobes were done by the handicrafts from local communities and the mortar mixture was recovered from the oldest habitant who remembered the exact place where his grandfather used to take out the earth to construct their houses at that time. Once more it was noticed the lack of trust in the materials, as it was necessary to realize laboratory exams (mechanical ones) to the earth and to the bamboo poles. These analysis assure the clients and the contractor that the material was safe and capable. In the earth tests it was proven that the earth Don Julio selected was the best one to be used.

A stone foundation and basement was constructed to support the load bearing adobe walls. So, the earth technique was used with all its potentiality, without the common vertical concrete reinforcements, to emphasis the enormous potentiality of the material where they are used properly, when its qualities and limits are respected.

On the back wall it was done an intervention right from the base foundation for wall reinforcement and stabilization of the center of gravity of the load-bearing element.

Due to the length of the walls, it was left a joint in every 12m and the same measures were respected in the interior steel structure that supports the roof. In fact, these joints contribute as aesthetic contemporary image solution, that replaces the traditional buttress, an important element in a high seismic zone like Oaxaca. These columns are also separated 50cm from the walls to avoid contact during the movements.

It was made a big effort to assure the times of construction in a way they could be competitive in the urban world. Traditionally, the adobe wall assented with earth mixture has to grow just one meter each time before it dries up, so it can consolidate and lose the same quantity of water without losing its structural homogeneity. To solve this issue it was used, once more, a mix of knowledge between the rural and contemporary techniques. It was used a mixture of sand and lime stabilized with 5% of cement, so it can dry more quickly and also give more security to the clients and the contractors.

To close the roof it was taken an inspiration from the rural and sub-urban low cost construction, using a thin metal sheet (coming from the tin cans in industrial production), commonly used to fence off land or little constructions. Cutting and painting the sheets was created a geometrical composition of eleven different colors that gives a contemporary aspect to the whole complex (Caeiro, 2013a).

It is also important to notice that all the 140 000 red bricks and 22 000 tiles used in the complex were manually produced in local communities, and demonstrated to have more quality than the industrial ones. Each red brick or tile is unique as they have the fingerprints of the craftsman that makes them unique pieces, giving the construction humanity and esthetic quality. The revalorization and promotion of their own materials is also an important issue for the local communities, so its traditions can endure through time, helping the community development and giving back money to the rural world. Through urban projects can be revitalized local

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*Figure 8. San Juan Mixtepec, Mixteca, Oaxaca, México [Autor]. Figure 9. Stone Intervention, Oaxaca [Author].*
economies instead of importing materials from other states or maintain the monopoly of big materials enterprises. This fact works not only towards social and architectural, but also cultural sustainability.

The whole complex was provided with water and energy feedback systems, using passive strategies as water collection (canalized and stored in underground tanks) and natural ventilation, created through a horizontal opening that runs all along the top of the adobe walls.

5. Conclusion

The described projects represent a good example of new construction that can be an inspiration to the self-constructors and new generation of architects. In fact it shows that is possible to build with sustainable principles, without leaving the old traditions.

It becomes clear the need of recuperating the old construction knowledge. This is only possible through a bilateral transfer of knowledge between town and village, which can be produced in many ways. Conferences, seminars, workshops and training practices (in which each everyone can contribute with their own experience) result fundamental for architects, servants, students and villagers. Local knowledge linked to well done construction is integrated and valued by the academic culture, while the rural reality of self-builders absorb correctly their own know how almost forgotten, connected with the new technologies and materials.

On the other hand, real built examples, as the constructions on top described, are needed in the actual society to demystify false beliefs about natural materials and vernacular techniques. The urban world has always influenced the rural thoughts and habits, so if 50 years ago the concrete tide spread all over the territory, now is time to release a new and more responsible tide, a sustainable one.

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Deformation of Masonry Structures of Libraries, Bayon in Angkor Thom

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Abstract

This paper provides a geotechnical mechanism that has caused vertical gap between stones on retaining structure for platform mound of “library structure” in Angkor, Cambodia. The formation of the gaps could be misinterpreted as sliding due to shear failure of the filled earth mound. Archaeological trench at the Northern library, Bayon revealed no such shear failure in the trenched section. Vertical gaps have developed along joints in the sandstone masonry of a retaining wall in the free-standing stone masonry structure. The wall retains a mound of compacted earth- and sand-filled foundations. The formation of the gaps was identified as horizontal expansion caused by wetting by rain under constant vertical load.

Keywords: Vertical gap, Masonry structure, Angkor, Library structure, Bayon temple

1. Introduction

Following the inter-governmental conference on Safeguarding Angkor in October 1993, Japanese Government Team for Safeguarding Angkor (JSA: Leader T. Nakagawa) was organized in 1994 and started study on the Angkor monuments in various areas of architecture, archaeology, geotechnical science, geology, petrology, conservation science, masonry, and others. So called “Library” in Angkor is an independent masonry structure that consists of upper masonry and foundation mound of compacted sand of height of 5m with retaining wall of stone blocks. It was not necessarily to store books and usually stands as one pair in front of a temple. Northern Library of Bayon, the central temple of Angkor Thom was selected as the first heritage structure for restoration work of JSA in Angkor. Skewed lines of crack on the side wall of the foundation of the Library monument had suggested sliding down outwards of both end of the foundation of the library. When the archaeological team completed a vertical section of the side porch, no shear lines were detected. Angkor provides many puzzles in geotechnical engineering. This paper provides general introduction of the restoration work and the secret mechanism of the apparent crack lines on the side wall of stone work.

2. Northern Library of Bayon Temple, Angkor Thom

The plan view of the Bayon temple is shown in Figure 1. Northern and Southern libraries stand in the eastern side of the temple. South side view is shown in Figure 2 with two photos of partial enlargement of both east and west ends. Figure 3 shows the south side view of the foundation wall in the west end. Gap line of stones from nearly top of the foundation to down onwards might suggest some sliding of the soil ground inside the retaining wall. Figure 4 also shows the widening of gaps between stones that continues west and downwards direction.

The upper structures were partially lost and the remained parts of the structures were heavily damaged. The detailed structure of the foundation platform was not known.
3. Monitoring structures

Monitoring of structural behavior was performed for several items of the Northern library. Some results of such monitoring are introduced here. A displacement gap sensor that is based upon strain gages were used as shown in Figure 5 (JSA Report, Y. Iwasaki (2000)).

A gap sensor was installed at horizontal gap between column stones that was caused by bending of a pillar inside the upper structure as shown in Figure 6 and Figure 7. Another gap sensor was installed at vertical gap between stones of retaining wall. The monitored results are shown in Figure 9 as well as monthly rainfall in 1995. The monitoring started in February 1995 of the end of dry season for one year until February 1996.

There are some common characteristics and significant difference between these gap movements of horizontal and vertical movements. In general, these gaps are somehow related with rainfall. The vertical and horizontal gaps increase with the rainfall. Vertical expansion during rainy season is found to return to the original position. On the contrary, the vertical gap is recorded to expand during rainy season and never return to the starting position in the following dry season.

![Diagram of Bayon Temple and Northern Library with labels for Northern and Southern Libraries.]

Figure 1. Bayon Temple.

![Images of Bayon Temple: Side View Northern Library; West end of south side; East end of south side of the Northern library, Bayon temple.]

Figure 2. Side View Northern Library.
Figure 3. West end of south side.
Figure 4. East end of south side of the Northern library, Bayon temple.
4. Trenched section of the foundation platform

Archaeological trench was carried out at the west side of the foundation platform of the Northern Library. Figure 10 shows vertical trenched section, which consists of compacted fill with retaining wall of laterite blocks and sand stones. The fill was well compacted layered sand. The compacted sand was surrounded by laterite blocks and the clayey filler was found at the boundary between fill and laterite blocks.

No shear sliding surface was identified behind the horizontal gap in the sand fill.

5. Deformation characteristics of platform of library structure

The vertical gap, which might be recognized as shear sliding in the platform foundation, was found not related with the sliding plane in the platform fill. If the gap is caused by sliding, some differential settlement should be observed between adjacent blocks. As a matter of fact, the horizontal line of stone surface keeps almost the same levels. The vertical gaps in the stone masonry structure are one of the deformation characteristics in the Library Structures in Angkor.
Figure 9. Gap monitoring result.

Figure 10. Trenched west-east section west end of Northern Library, Bayon (JSA Report, Komaki, 2000).
5.1. Load transformation to platform foundation

Figure 11 shows stress flow of load from the upper structure to lower platform foundation. The load of the upper structure is transferred through stone column to the foundation. The load of the stone beneath the column is transferred to sand stone and laterite block at level A. The bottom of the laterite block at level B is supported by filled ground. The sand stone and laterite block of the retaining wall is partially supported by filled soil and forces tends to spreading out as shown in Figure 11. As explained above, the basic structural arrangements of stone and laterite elements had a tendency to induce horizontal displacement.

![Diagram of load transfer](image_url)

**Figure 11.** Load transfer from upper structure to platform foundation.

5.2. Horizontal expansion due to wetting

As shown in Figure 8, it is found the vertical gap of the retaining wall and the horizontal gap of the stone column under bending state expanded during rainy season. The mechanisms of these movements are considered as related with wetting and drying states of fill and stones.

5.2.1. Vertical gap

The fundamental characteristic of soil under a constant vertical stress is the key element to understand the change of the vertical gap of Angkor monument. When a soil is confined by stone block as shown in Figure 11, horizontal force between the soil and stone block depends the magnitude of vertical load of the column. During dry season, soil becomes dry with negative pore pressure developed in soil particle, which attracts soil bond each other. When rain infiltrates into the filled soil in rainy season, the negative suction pressure of water in the fill becomes smaller and finally disappears. When the suction pressure disappears, soil will lose the bonding strength between soil particles and will become soften. According to these softening characteristic of filled soil caused by infiltration of rainy water into the filled soil, horizontal force between the fill and stone shall become increase during the rainy season. The stone shown in Figure 8 and Figure 11 are positioned at the outer surface.
of the retaining wall that does not contact with filled soil in the concerned direction. The horizontal displacement takes place at the stones inside the wall that have real contact with fill was moved outwards without any gap.

Figure 12 shows a schematic process of seasonal changes of successive action of rain and corresponding response of stone and filled soil for different positions of inside and outside of the retaining wall. In Figure 6, on another side of the retaining wall, the same vertical gap lines are identified.

5.2.2. Horizontal gap

Horizontal gap shown in Figure 7 was caused by bending deformation of the inclined stone column and difficult to relate any specific movement of the stone and/or filled material. However, the vertical movement of the monitored point returned to the original position.

6. Conclusions

Vertical gaps have developed along joints in the sandstone masonry of a retaining wall in the free-standing stone masonry structure referred to as the “library” in Angkor. The wall retains a mound of compacted earth-and sand-filled foundations. The formation of the gaps could be misinterpreted as sliding due to shear failure of the filled earth mound.

In fact, the development of the gaps can be attributed to horizontal expansion of filled earth under vertical loading of a column during rainy season. However, the vertical gaps between the surface stones cannot be directly related to the expansion of the filled mound but rather to associated movements with stones within the foundations that are in direct contact with expanded filled mound.

References

A Study on Conservative Material for the Bas-Reliefs of the Bayon Temple in Angkor Monuments

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Abstract

The gallery wall on which the Bas-reliefs are etched of the Bayon temple in Angkor is made of sandstones. The deterioration caused by penetration of rainwater or groundwater is being accelerated and these sandstones are in serious condition. The aim of this research is to select a water repellent agent and an agent for reinforcing and consolidated sandstone pieces that compose the bas-relief wall. Three type of consolidation products and nine species of water repellent agents were taken. And for cracks and lost parts, eight type of the restorative materials for repair and forming for Bas-relief are to be selected. These samples were exposed since 2007. As results, the weather ability of each agents are cleared with some measurements which are water absorption, surface hardness test and ultrasonic propagation. A certain level of evaluation of consolidation product and water-repellent agent has been obtained. The hardness of consolidation product is returning to the pre-treatment state after six years of exposure. Effect of each water-repellent agent was well maintained even though the surface hardness is returning to the pre-treatment state in the exposure test using combination of consolidation product and water-repellent agent. However, for the test piece treated with water-repellent agent only, water-repellent effect started to vary after three years of exposure. For aged change of restorative materials for repair and forming, surface treatment is required to prevent collapse and discoloration. It was found that application of water-repellent agent only is not effective and that the role of surface treatment agent is important. Microbial flora that is easy to adhere at the early stage was revealed. Many Ascomycota groups are also detected by DNA analysis as initial microorganism which attached the surface of test pieces.

Keywords: Bas-relief, Sandstone, Consolidants, Water repellents, Weather ability.

1. Introduction

The threats that endanger the heritage site becoming more and more diverse. Before the site was put into use, the materials of heritage had already suffered deterioration under various natural laws. But when the people started to take advantage of the heritage as a resource and utilities, the deterioration rate is accelerated, and unknown threats arise. There is presenting a great problematic in front of our eyes. There are two ways for the role of practical conservation science on sites. The first one is to establish a conservation method that concerned with dispositions like sorting out materials for conservation and restoration methods. The second one is to carry out a preventative conservation as a precaution technique.

Figure 1 shows the one of the deterioration of relief in Bayon. In this case, a restoration of the peeled off part of this figure and also making some preventative dispositions for the rest of it to prevent from further deteriorations.

The Bas-reliefs of Bayon temple in Angkor, Cambodia are serious condition due to multiple use and activities on the site. In the case of the Bayon bas-reliefs, the repair must not give an unnatural visual impression and thus further attention is required. Also, in principle, reversible preservation agents that can restore to the
original state are used as needed. The following basic policies are set in line with these concepts of the cultural property restoration (Sawada et al. 2011):

(a) Conservation and restoration are not to detract the artistic quality or the sublime aesthetic value of the bas-reliefs.

(b) With regards to the structure of the entire gallery including the bas-reliefs, measures to prevent structural loosening and collapsing will be taken. The deterioration factors of the individual rock that composes the structure are to be determined and measures to preserve the rocks are to be considered. Specifically, measures to avoid the impact of water on the bas-reliefs will be taken by preventing rainwater penetration and improving water shielding and discharging functions of behind the gallery and the floor.

(c) When removing salt or other deposits, inquiline microorganisms and grime caused by bat feces attached to the surface of the bas-reliefs; the first priority is given to conserving the bas-reliefs, excessive removing treatment is to be avoided and a method that will not detract the grace and the texture of the bas-reliefs is to be examined.

(d) The restoration sciences that are matched to restoring the Bayon temple bas-reliefs are to be established. Furthermore, with a view to applying them to restoration of other ruins, research on the development of preservation agents and execution techniques is to be conducted.

(e) Human resource development of experts for conservation and restoration in Cambodia and establishment of a public institution will be brought up through the series of projects.

Various tests have been carried out to make a selection of preservative and restorative materials suitable for the sandstone used for the bas-reliefs of the Bayon temple in Angkor monuments since 2007. In this publication, results of application tests of toughening materials and various water-repellant agents are reported. Along with this test, evaluation tests of artificial rocks as repair and forming material that are applicable to sandstone in various textures used for the relics were carried out in the Bayon temple. This restorative material for repair and forming was made from grinded sandstone mixed with resin at various mixture ratios, and in addition, the surface was reinforced by treatment of water-repellent agents and consolidation products.

2. Test pieces and agents for exposure test

Test pieces of sandstone were collected from the estimated area around Siem Reap where Angkor monuments are located as original source and the sandstone was shaped into a cylinder (45mm in diameter and 100mm in length). 96 pieces for the exposure test of consolidation products and 61 pieces for the test of water repellent agents were made. At the time of shaping, in consideration of joint of sandstone, the cylinder was shaped so as the direction of the typical joint pattern of sandstone is horizontal and perpendicular to the length direction of the cylinder. Density of a test piece (cylinder) is around 2.33 to 2.34g/cm$^3$, and the water absorption is approximately 4.2%. Table 1 shows the physical properties of test pieces.

The region where the Bayon temple is located is the subtropical zone with much rain. When selecting water repellent agents, it was decided to pick agents of silane series taking into account workability in hot and humidity conditions as well as easiness to handle and safety. Silicate ester which is used worldwide was selected as a consolidation product. Ingredients of monomer component and polymer component were individually prepared and each consolidation products were made uniquely with the mixture ratio shown in Table 2. Bayon-S in the table 2 is the standard one. Bayon-M means the consolidation product with higher monomer than the Bayon-S, Bayon-P agent is the toughening one with higher polymer component ratio. These differ in the crystal growth rate and the crystal size according to the environmental condition at the time of use.

For the water repellent treatment, some of them was done in combination with consolidation product (Table 3), and using water repellent agents only (Table 4). Water absorption, the surface hardness (Equotip Hardness tester; L-value) and the ultrasonic propagation were measured as the assessment of these pieces and agents. Because the combination used with the consolidation product was a premise for the conservation of bas-reliefs and some of the water repellent agents has nano-crystal, the surface hardness of the water repellent test pieces was measured.
Restorative material for repair and forming that are to be used as restoration material of supplemental aesthetic, which can be applied to sandstones with various textures used for the bas-reliefs, are under the exposure test in the Bayon temple. To make restorative materials that form absorption and desorption of moisture, the material was made from grinded sandstone mixed with resin at various mixture ratios, and in addition, the surface was reinforced by treatment of water-repellent agents and consolidation products. SITE-FX (LN Technical Lab) was used for the resin. SITE FX is resin component based on 100% epoxy resin and special emulsifiers. SITE FX is capable of making the emulsified solution of optional solid content. Specifications of the restorative materials are shown in Table 5. SPT is acrylic resin emulsified solution including acrylic-styrene copolymer. The exposure stands are located in between outer corridor and inner corridor on the south side of the Bayon temple, the height is about 2m from ground.

Table 1. Physical property of test pieces.

<table>
<thead>
<tr>
<th></th>
<th>Density (g/cm³)</th>
<th>Water Absorption (%)</th>
<th>Surface Hardness (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Average</td>
<td>2.33</td>
<td>4.21</td>
<td>515.2</td>
</tr>
<tr>
<td>H Average</td>
<td>2.31</td>
<td>4.23</td>
<td>520.1</td>
</tr>
<tr>
<td>V Average</td>
<td>2.34</td>
<td>4.21</td>
<td>513.5</td>
</tr>
</tbody>
</table>

H: Horizontal joint in height direction V: vertical joint in height direction

Table 2. Mixture ratio and specific gravity of consolidation products.

<table>
<thead>
<tr>
<th>Consolidation products</th>
<th>Blending ratio</th>
<th>Specific gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bayon-P</td>
<td>15 : 85</td>
<td>1.017</td>
</tr>
<tr>
<td>Bayon-S</td>
<td>25 : 75</td>
<td>1.006</td>
</tr>
<tr>
<td>Bayon-M</td>
<td>40 : 60</td>
<td>0.990</td>
</tr>
<tr>
<td>Site SX-R/B</td>
<td>Closely resembling Bayon-S</td>
<td>1.005</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Water repellent (trade name)</th>
<th>Composition</th>
<th>Sample name</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIGHT SILANE Z</td>
<td>Silane Emulsion</td>
<td>Bayon-Sb</td>
</tr>
<tr>
<td>OBH</td>
<td>Mixture the silane monomer and oligomer</td>
<td>Bayon-Sc</td>
</tr>
<tr>
<td>Protectosil 40S</td>
<td>Silane Monomer</td>
<td>Bayon-Sd</td>
</tr>
</tbody>
</table>

Table 4. Water repellants tested in test pieces without consolidation products from 2008.

<table>
<thead>
<tr>
<th>Water repellent (trade name)</th>
<th>Composition</th>
<th>Sample name</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIGHT SILANE Z</td>
<td>Silane Emulsion</td>
<td>Tight Silane</td>
</tr>
<tr>
<td>Wacker 290</td>
<td>Silane Oligomer</td>
<td>290</td>
</tr>
<tr>
<td>Protectosil BHN</td>
<td>Silane Monomer</td>
<td>BHN</td>
</tr>
<tr>
<td>ADESSO WR-1</td>
<td>Nano Silica</td>
<td>WR-1</td>
</tr>
</tbody>
</table>

Table 5. Specifications of restorative materials.

<table>
<thead>
<tr>
<th>Name</th>
<th>Component of Site FX</th>
<th>Ratio of mixing, Site FX to sandstone powder</th>
<th>Surface Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>27.5%</td>
<td>1:4.5</td>
<td>Surface reinforcing Material SPT (15%) + Angkor sandstone powder</td>
</tr>
<tr>
<td>B</td>
<td>32.5%</td>
<td>1:5.5</td>
<td>Site FX (32.5%)</td>
</tr>
<tr>
<td>C</td>
<td>37.5%</td>
<td>1:5.0</td>
<td>B72(8%) + Angkor sandstone powder</td>
</tr>
<tr>
<td>D</td>
<td>37.5%</td>
<td>1:3.5</td>
<td>Surface reinforcing Material SPT (15%)</td>
</tr>
<tr>
<td>E</td>
<td>37.5%</td>
<td>1:4.0</td>
<td>B72(8%) coating</td>
</tr>
<tr>
<td>F</td>
<td>37.5%</td>
<td>1:4.5</td>
<td>Without treatment</td>
</tr>
<tr>
<td>G</td>
<td>37.5%</td>
<td>1:4.2</td>
<td>Silicate sand + Acryl-silicone coating</td>
</tr>
<tr>
<td>H</td>
<td>40.0%</td>
<td>1:4.5</td>
<td>Water repellent BHN coating</td>
</tr>
</tbody>
</table>
3. Results and discussions

3.1. Consolidation products

Figure 2 shows the water absorption of the test pieces after six years of exposure from 2007 (before treatment) to 2013. Though the water absorption of the test piece treated with consolidation product only is about 1% smaller than that of untreated test piece (original), equilibrium state has been maintained for the last several years. The test piece treated with water-repellent as well as consolidation product has maintained water-repellent effect with the water absorption of 0.5% to 1.2%. The water absorption behavior of these test pieces after three years of exposure is shown in Figure 3. Since the test piece treated with consolidation product draws a curve of water absorption similar to that of untreated test piece, it could be assumed that the both water absorption processes are the same. Impact of consolidant on water absorption mechanism is assumed to be small.

At the site, surface hardness was measured by using a hardness tester. This is a measurement tool that can measure surface hardness of materials by bounce of a small steel ball fallen from a certain height. By using this tool, hardness of materials can be easily measured at site. Figure 4 shows the graph showing aged change of the hardness(L-value) of the test piece treated with consolidant. The hardness of untreated test piece decreased by 20L in one year and has been still decreasing since then. On the other hand, the L-value of the hardness of the test piece impregnated with consolidation product elevated approximately 30L to 50L, and it was found that the gradient of the subsequent decrease of hardness is similar to that of the untreated test piece. Detailed measurement was carried out for a part of test pieces brought back to Japan. The results showed that some samples in moisture condition have L-value nearly 100 lower than that of dried condition. The degradation of strength has become larger after five years of exposure and it returned to the pre-treatment state in 2013, after six years of exposure. However, since considerable epiphytic adhered on the test pieces, the result is assumed to
be affected by the epiphytic covered over the measurement surface. Regarding the difference between exposure surface and non-exposure surface, it was found that the characteristics of each consolidation products varies according to surrounding environment since there was a tendency that the value of surface hardness of non-exposure surface is larger than the other. (Matsui et al. 2012)

3.2. Water-repellents agents

There was a phenomenon that the water absorption of test pieces, including untreated test piece (Original), decreased at the beginning of the test (Figure 5). It was found that the surface hardness of the untreated test piece decreased year by year by about 10% during 4 years of exposure (Figure 6). On the other hand, the surface hardness of the test piece treated with water-repellent Wacker290 was maintained until 2011 and the water absorption was also maintained at low level. This fact proves the outstanding water-repellent effect of the treatment. Wacker290 had displayed strong wet color for 4 years after its application; after that, however, the color has been stable in a color tone close to that of the test piece before treatment. Since Angkor region had record-breaking heavy rainfall in 2011, black-colored epiphytic microorganism was found in test pieces other than those treated with Wacker290 (Matsui et al. 2013).

It was found that the dirt adherent to the test pieces and artificial rocks were black filamentous microorganism (Figure 7, 8) and grayish-black granular microorganism. Both 2 types of microorganism were just adhered to the surface of the test pieces, and the black filamentous microorganism overlapped one another in some parts and formed a sort of mat with a thickness of about 0.5mm. There was a possibility that the filamentous microorganism could be fungi or algae and the granular microorganism could be fungi or algae or bacteria.

![Figure 5. Water absorption of test pieces with water repellent agents.](image)

![Figure 6. Surface hardness of test pieces with water repellent agents.](image)

![Figure 7. The test piece adhered filamentous microorganism.](image)

![Figure 8. Black filamentous microorganism on the test piece.](image)
Microbial flora that is easy to adhere at the early stage was revealed. Microorganism samples were carefully collected by adhesive films. Their DNA were extracted using DNeasy Plant Mini Kit (QIAGEN) after crushing with a cell disrupter (Multibeads shocker, YASUI KIKAI). The variable D1/D2 region of nuclear 26-8S rDNA was amplified using Fungal rDNA (D1/D2) PCR Kit (TaKaRa) and cloned into pGEM-T Easy vector (Promega) according to the manufacturer’s instructions. Eight clones from each sample were selected and subjected to sequencing in the Biotechnology Center at Akita Prefectural University. In the state that many kinds of microbial were mixed and interact with each other, many Ascomycota derived from soil were detected and fungi consists of lichens and algae were detected in some test pieces. There are reports on the existence of microbial flora in Bayon temple, specifically about bacteria and fungi (Kusumi et al. 2011) and about lichens (Kawasaki et al. 2013).

The water-repellent agent using a new material “Nano-silica” has given an impression that its water-repellent effect was inferior to other water-repellent agents. Monomer series water-repellent agents also had a tendency that the water absorption increase. Persistence of water-repellent effect must be followed up. Emulsion series and Oligomer series agents have good water-repellent effect, and emulsion series exhibited hardness close to original. As with consolidation products, different material of water-repellent agent that received a certain level of evaluation at exposure tests must be used according to the situation of sites, and assessment of deterioration of reliefs and development of application methods are challenges in the future.

Figure 9. Restorative materials exposed from 2008. Lower half of samples were wrapped in aluminum foil.
3.3. Restorative materials for repair and forming

We investigated the surface texture of the restorative materials and its damage mainly to keep artistic value of bas-reliefs. Figure 9 shows the status of the restorative materials after five years of exposure from 2008. Artificial rock F is a sample without surface treatment. The surface layers ended up being significantly exfoliated, the boundary with unexposed surface became uneven, and significant change in color was observed. This indicates the importance of surface treatment agent. The surface of Artificial rock A became rough to a certain degree. Surface treatment agent still remained but adherence of some dirt was observed. For artificial rock B whose surface was treated with SITE-FX, the surface-treated layers were mostly exfoliated and the boundary with untreated surface became uneven. Artificial rock C is a sample to which acrylic Paraloid B72 (8%) mixed with sandstone powder was applied as surface treatment agent. Though partial exfoliation of surface treatment agent was confirmed. The surface of artificial rock D was relatively smooth, however, significant degree of change in color was observed. Therefore attention should be paid when it is used as a restorative material. To artificial rock E, acrylic Paraloid B72 that was applied to artificial rock C as surface treatment agent was also applied, and this is a sample to which only resin (Paraloid B72) was applied without mixing sandstone powder. In comparison with artificial rock C, the surface of artificial rock E was exfoliated and the surface layer was disappeared. Moreover, significant change in color was observed. It was decided that artificial rock G was considered as the most highly evaluated restorative material in the test conducted this time (Figure 10). Roughness of the surface was hardly observed. However, degree of adherence of dirt is a challenge in the future. Artificial rock H is a sample to which water-repellent BHN was applied for surface treatment. Some exfoliation on the surface was observed in this sample.

For aged change of restorative materials for repair and forming, surface treatment is required to prevent collapse and discoloration. It was found that application of water-repellent agent only is not effective and that the role of surface treatment agent is important. However, it was found that some surface treatment methods are easy to cause discoloration while it can maintain surface conditions. Among them, surface treatment methods using acryl-silicone could maintain surface conditions and showed little discoloration.

![Figure 10. Sample G and F from a lateral view.](image)

4. Conclusions

Effects of consolidation products and water-repellent agents for sandstone of Bayon Temple was confirmed by exposure tests and quantitative evaluation was carried out. Weather resistance capability of consolidation products and water-repellent agents are being revealed by five years (six years for consolidant) of exposure test using sandstone. Regarding restorative materials for repair and forming, there was a large difference in test results according to surface treatment methods, which showed the importance of surface treatment agent, and knowledge of suitable specifications for Bayon Temple was obtained at the same time. The investigation of physical and mechanical properties of materials will be investigated in next step because we made mention of only the texture of surface of restorative materials in this research. It was found that it is important to use appropriate preservation material according to conditions of sites. Determination of deterioration state of reliefs and development application methods are challenges in the future.
In parallel to these studies, characteristics of annual climate change in each corridor where reliefs of the Bayon Temple are located have been revealed by micrometeorology observations since 2007. Further investigation will be done continuously in the future so as to enable appropriate selection of preservation materials according to deterioration state and surrounding environment of the reliefs.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number 25257303,22300305 and JASA(JAPAN-APSARA Safeguarding Angkor). The DNA analysis was carried out with the cooperation of Dr. Kojiro HARA and Dr. Yoshikazu YAMAMOTO (Akita Prefectural University).

References


Previous Archaeological Surveys on the Foundation Structure of the Pyramid Shape Temples in Angkor Monuments

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Abstract

Several stepped pyramid shape of the temple structure has been left in the Angkor monument. Many of them are located on the flatland, and the inner structure of the high platform is little known. Unlike the structure at the Egyptian pyramid which was fully constructed by stone masonry, pyramid shape of the Angkor monuments might be constructed of the combined materials such as surface stone, and inner laterite and compacted soil fill. Except for this Baphuon temple, some of the pyramid shape temples with high platform; Prasat Thom in Koh Ker, Angkor Wat, and Bayon, are still stable condition. Although some part of the surface stones have been collapsed from the original position, remarkable structural deformation is not allowed. It is highly curious point to clarify the inner structure of the stepped platform. This paper described on the previous excavation surveys at the central pit of these pyramid shaped temples in order to find the clue on the inner structure.

Keywords: Bayon, Angkor monuments, Cambodia, Foundation structure, Pyramid shaped temple

1. Introduction

Bayon temple was built in the center of the royal capital, Angkor Thom, by king Jayavarman VII at the end of the 12th century. The Central Tower and the smaller towers are located in the center of the pyramid styled temple. The towers are standing on the central terrace, which is about 10m high. Eight sub towers are positioned around the Central Tower, which has a height of 43m above ground. There are other towers located on the east front side, which are antechambers or worship chambers, connected with the Central Tower. In Khmer architecture, the Central Tower of Bayon temple is the second highest after the one in Angkor Wat. This cannot be seen in any other temple, and gives a dignified and established impression as if it was the center of the huge Angkor Empire.

The Bayon temple was initially built as a Buddhist temple with a 4.7m tall sedentary Buddha statue housed in the main chamber. Later the statue was destroyed and replaced with a different god statue. The Buddha statue, which is thought to have been housed in the main chamber, was found in the central vertical hole by l'Ecole Francaise d'Extreme Orient (EFEO) during the excavation in 1933. After the examination, the excavation hole was backfilled. There are no records about the details of the backfilling work.

2. Previous restoration of the Central Tower by EFEO

Since the last century, the research on Bayon Temple has been conducted under different aspects including architecture, art history, and inscriptions. In the field of archaeology, from 1919, various results have been reportPast archaeological survey was summarized in some articles, such as Parmentier (1927, 1936), Marchal (1937), Dumarçay (1973), Mannika (1996), Jacques (1998), Nishimoto (2004), Kong et al. (2005), Cunin (2007), and Shimoda (2009). Since around 1911, minor works such as relocation of fallen stones and cutting trees have
been carried out. However, due to an incident in 1932 when a part of the Central Tower collapsed, reinforcement work on the Central Tower started in 1933.

Old photographs taken before the restoration work of EFEO show the severe displacement of the stones and large gap openings at the top part of the Central Tower (Photo 1). Scaffolding was installed on the upper part of the Central Tower (Photo 2), and partial dismantling and reconstruction works were carried out. Displaced stone blocks were recovered to the original position and vertical gap openings were closed by this operation. Gap openings were filled by cement mortar where they were not reconstructed (Photo 3). Hazardous areas were supported by reinforcement concrete posts and beams (Photo 4), and iron bands, and connecting bars were installed inside the tower (Photo 5). According to "Rapport d’Angkor"(EFEO 1933a), the big scale reinforcement work started in January 1933 was completed in August 1933 and excavation work in the main chamber followed.
3. Previous archaeological survey at the central pit in the Central Tower and East Chamber (Tower 12) by EFEO

The following is a summary of the excavation work described in "Rapport d'Angkor". The examination by EFEO was conducted under the instructions of a conservator, Trouve, for two months. A vertical hole was discovered below the floor surface of the Central Tower and they dug 14m down (Figure 1). A Buddha statue, which is thought to have been a principal image in Bayon temple, and many stone fragments from the statue were found (enshrined in Vihear Prampi Loveng now). From this it became obvious that this hole had been looted before. They continued digging down for one more meter. They also dug horizontally in east, west and south directions at a depth of 12.5 m from the top. In the horizontal directions they reached a wall made of "sandstone block offcuts with four corners", which is recognized as "the edge of the old vertical hole". The discovered wall is directly below the wall of the main chamber and it is suggested that some frame might exist in the platform beneath the superstructure.

**Figure 1.** Record of the Central Tower based on excavation by Trouve in 1933 (drawing - EFEO 3292) [original description is in French].
As the examination was conducted during the rainy season, groundwater rose to the point of 12.5 m depth in late September and the excavation work to the natural ground level had to be cancelled. After the examination, the hole was filled to a depth of 2 m from the floor surface and they waited for the opportunity of re-examination. But this plan was abandoned due to the death of the conservator. According to the EFEO records, Trouve filled to a depth of 2 m after the excavation in 1933 and a conservator, Marchal, filled the remaining 2 m later.

In 1937 Marchal also conducted excavation work in the 12th tower, which is the east chamber of the central tower, for the purpose of examining the foundation structure. In this examination, they dug 6.3 m deep from the floor surface. As a result, 1.34 m high masonry laterite was found inside of a platform. The compacted soil layer, which is composed of sand and gravel, was found below it and sandstone blocks were discovered at a depth of around 4 m from the floor surface of the tower. While the laterites on the south side are four layers, the laterites on the north side are only two layers. This asymmetric structure is notable (Figure 2, Marchal 1937: 648, Fig. 58).

These two examinations in the central tower and the 12th tower are all archaeological excavations conducted in the past under the Central Tower of Bayon.

![Figure 2. Record of the excavation in the Tower 12 by Marchal in 1937](original description is in French).

4. Study on the backfill condition after the excavation survey at the Central Tower of Bayon

In order to confirm the previous backfilling work of the Central Pit by EFEO, Japan APSARA Safeguarding Angkor (Co. Directed by Dr. Nakagawa Takeshi and Dr. Ros Borath) carried out the excavation survey at the northern half of the Main Chamber in 2008. Below is a summary on the survey. Analysis of the top 2 m backfilled by Marchal and the lower layers backfilled by Trouve are individually reported below.

4.1. The upper layer of the backfill

The current paving stones are composed of two layers of flat sandstones with a thickness between 20 cm and 30 cm. These flat stones were collected around the area and paved on top of the backfill. Some stones of the
floor surface of the main chamber still have their original shape. These are the sandstones beneath the walls and the sills of the four entrances. However, the inner paving stones, which include decorative ones with engraving from each construction, are small, irregular and paved carelessly. It is presumed that scattered or temporarily arranged stones were collected and used for paving the inner parts after the excavation by EFEO. There are two pillar holes on the east side and one on the west center side in the original floor stones. Therefore, it is presumed that a wooden sheath hall or something similar was placed around the statue in the beginning.

The joints between the paving stones are filled with earth and sand. This loose black colored soil (humus) is contaminated and seen until 40 cm depth from the paving stone's surface. A 500 Vietnamese dollar coin (made in 2003) and a 10 Thai baht coin (made in 2003) were found below the sandstone pedestal of the current Buddha statue and on the top surface of the sandstone. An American 1 cent coin (made in 1976), a Thai 10 baht coin (made in 1992), a Japanese 100 yen coin (made in 1978), a small copper Buddha statue (presumed recent), a tin can (Thai, Tiger beer) and a lot of trash like plastic bags and plastic straws were found between the sandstone paving. Some of the paved stones in the center have an irregular shape. This is because some of the stones were paved in recent years. It seems that trash and coins mixed with the soil when the stones were replaced. Even 10 cm below the paving stones, a lot of trash, together with the contaminated black soil, is seen.

Under the current floor surface, between 40 cm and 225 cm deep, gunmetal brown soil containing sandstones and gravel (20 to 30 cm) was found. The soil density was low and had some cavities. It seems that the soil of the upper layer entered into these cavities. Therefore, it is also presumed that the upper portion of the vertical hole sunk around 10 cm after the backfill. The backfilled ground is very unstable and is difficult to dig where the excavation was conducted. Because of this, the site of the excavation had unstable slopes and backfilled soil slid down from higher parts into the area being excavated.

In the upper portion of the backfill, pieces of china, glass and iron goods were found. Most of the china was modern from China, Thailand, Europe and so on. On the other hand, little artifacts were seen in the lower part of the backfill. A part of the statue and the engravings had been buried together with gravel. Most of the gravel was made of sandstone and clearly different from the gravel contained in the compacted soil beneath the original wall. It is presumed that stones scattered around the central tower were used.

4.2. The lower layer of the backfill

The excavation was cancelled 225cm below the current floor surface because of the risk of falling compacted soil beneath the wall and gravel around the excavation hole. But it was found out that the stratum there contained sandy soil and less gravel. It is clearly different from the upper layer. With this examination result and the record from EFEO, it is believed that the soil more than 225cm below the floor surface is the one backfilled by Trouve, while Marchal, who was a successor, backfilled between a depth of 40 cm and 225cm.

4.3. The original foundation structure directly beneath the wall

During the excavation in the main chamber, one to two layers of laterite, which are each about 30 cm thick, were confirmed directly beneath the lowest layer of the sandstone wall. The interior side of the laterite was weak and rounded. It is presumed that weathering and deterioration might be one of the causes as that side was exposed for a while during excavation work in the past or when it was looted. The laterite support power of 770 kPa was measured by a Yamanaka soil hardness meter.

On the west side, as documented by the EFEO records, a large amount of compacted soil was removed below the laterite creating an overhang. No masonry structure could be confirmed below the laterite layers. Due to the threat of a possible collapse of destabilized compacted soil, even in the excavation area which was dug 2 m deep, only the upper part was examined. The compacted soil below the laterite layer was composed of brown sandy soil, which contained 20 cm large breccia and a thin 3-5 cm layer of silty clay. The grain size of the brown sandy soil was medium. The breccia was not sandstone, but a kind of conglomerate rock as was confirmed during the restoration works on the Northern and Southern Library of Bayon temple. Therefore, it is
clear that the compacted soil was not made from the offcuts which were produced during processing stone materials for building the temple, but from materials which were prepared in advance for the interior platform. The water content was about 5% and the support power of around 800 kPa was measured using a Yamanaka soil hardness meter.

In Khmer architecture, the laterite blocks used as a base are often piled outwards in a staircase pattern. Therefore, it was expected that the lower layer of laterite is indented to the middle of the block above. For this reason, a hand auger was horizontally inserted into the surface of the compacted soil during the first and the second examination in order to confirm the existence of stone material directly beneath the blocks of the wall. There were some parts where we could drill through the compacted soil wall into a next chamber. In other parts we were not able not proceed with drilling since the hand auger hit stone. It was presumed that these stones were gravel embedded in the compacted soil. This suggests that the masonry foundation structure, which supports the wall directly, does not exist beneath the wall. It is possible that the wall has a simple structure with one layer of laterite on top of the compacted soil.

5. Foundation structure inside the platform of the pyramid shape of Khmer temples

In some pyramid shaped temples on sites of Angkor remains, like Bayon temple, have been conducted the archaeological survey in the central tower in the past. The examination to bore the vertical hole from the top layer of the pyramid in Bakong temple was conducted by EFEO between October and December 1936. The height of the pyramid top of Bakong temple is about 15 m above the surrounding ground (Figure 3). From this point, the vertical digging was conducted down to a depth of about 20 m, which means around 5 m lower than the surrounding ground.

An original vertical hole, which had been looted in the past, was discovered. This hole had a laterite masonry retaining wall. The examination was performed along the hole while removing sandstone elements piled in the hole. The entrance to the hole was a square with roughly 2 m edge length. Then, an irregular square shaped hole with an edge length of 1.5 m continued below. In the vertical hole, elements from a sandstone sanctuary, built on the top of the pyramid in the past, were piled up almost until the bottom of the hole.

Brick fragments were found only at the bottom. Because of the discovery of those brick fragment at the bottom, an EFEO conservator presumed that a brick-made sanctuary was originally on the top of the pyramid, however it was replaced by the sandstone-made sanctuary later (EFEO 1936). Until a depth of 18 m, shaped laterite blocks as retaining wall existed. Below this, only unformed crude laterite blocks were found. It is not clear whether the hole was filled with compacted soil or empty when the temple was built. But it seems that the vertical hole was planned to have a very stable structure as no reinforcement was needed during the digging.

Figure 3. The excavation record of central hole, Bakong Temple (EFEO 2027A, Rapport 1936) [original description is in French].
Likewise Bakong temple, the Prang of the central temple Prasat Thom at Koh Ker is also an example of a temple with a clear vertical hole. The vertical hole discovered there has also a stone masonry retaining wall. Ak Yom temple is an example for a temple with a basement below a pyramid-shaped platform, although no vertical hole has been found yet (EFEO 1933b). The basement is made from tile masonry walls and floor. The tile layered ceiling has a corbelled vault shape (Figure 4).

In Angkor Wat, excavation works in the central tower were conducted in 1934 and 1935. In the excavation work in 1934, a hole was dug until a depth of 16.4 m (19.6 m depth with boring survey) from the floor surface, but it was cancelled as groundwater started to rise at that point. The examination was carried out again in the dry season the following year and the hole was dug until a depth of 25.25 m (27.75 m with boring survey) at that time. Through these surveys, no vertical hole had been discovered in previous EFEO excavation works (Figure 5). It is a very rare temple which has never been looted as compared to other remains in Angkor. Therefore, the existence of a vertical hole with reinforced retaining walls is not always found in pyramid-shaped temples and we conclude that there is no vertical hole in Bayon temple originally. However, a basement for the enshrining of ritual implements or others might exist even if it is not connected with a vertical hole.
6. Further studies on the foundation structure

Several pyramid shape of the temple structure has been left in the Angkor monument. Many of them are located on the flatland, and the inner structure of the high platform is little known. Unlike the structure at the Egyptian pyramid which was fully constructed by stone masonry, pyramid shape of the Angkor monuments might be constructed of the combined materials such as surface stone, and inner laterite and compacted soil fill. One of the pyramid shape temple, Baphuon which has the highest and steep platform structure, was recently completed its restoration project, and three layers structure was confirmed.

Except for this Baphuon temple, some of the pyramid shape temples with high platform; Prasat Thom in Koh Ker, Angkor Wat, and Bayon, are still stable condition. Although some part of the surface stones have been collapsed from the original position, remarkable structural deformation is not allowed. It is highly curious point to clarify the detailed inner structure of the stepped platform of these structures. This paper described on the previous excavation surveys at the central pit of these temples in order to elucidate the inner structure. It is strongly required to deal with the reinforcement of the loose backfill in the Central Pit of the Bayon temple with reference to these past researches on the resembled Khmer structures.

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A Study of Production Techniques of Bricks from the Royal Tomb of King Muryeong Using Nondestructive Analysis

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Abstract
This study examined the production techniques of bricks using nondestructive analysis and compared the results of mineralogical and geochemical analyses to recognize the significance and limits of nondestructive methods. The results of magnetic susceptibility, ultrasonic velocity and water absorption measurements provided major information on the provenance, compactness and weathering degree related to the firing temperature. Comparing the mineralogical and geochemical results of the bricks, it could be assumed that bricks from the royal tomb of King Muryeong were made of same raw materials and fired at 1,000 to 1,200 °C. It was also identified by the X-ray radiography observation that the clay was filled in the pattern side of the cast and pressured first and then other parts were filled with clay in the brick making process.

Keywords: Brick, Nondestructive analysis, Provenance, Firing temperature, Production technique

1. Introduction

Bricks are one of the most important architectural materials which have been used in making tombs, pagodas, walls and floors of the building structures since 1st century B.C. in Korea. Especially ancient bricks used for architectures of the kings and the noblesse were fired at high temperature and shaped with various patterns and inscriptions.

In the study of the production techniques of these bricks, it is the most effective to investigate the physical, mineralogical and geochemical approach. However, the nondestructive analyses were often chosen despite of their low accuracy because sampling from architectural heritage was difficult.

This study examined the production techniques – the estimation of provenance, firing temperature and shaping techniques of bricks - using nondestructive analysis focusing the physical properties of bricks and compared the mineralogical and geochemical results to recognize the significance and limits of nondestructive methods.

2. Samples and methods

The royal tomb of King Muryeong[462–523], the research site, is located in the Songsanri tomb complex, Gongju, which is the representative brick chamber tomb constructed during Ungjin period of Baekje [18B.C.–660A.D.]. This tomb consisted of rectangular shaped room and entrance passage and was made of about 25 kinds of bricks with different patterns and inscriptions (Figure 1).

This study selected 23 bricks as a reference brick, which remained a whole shape and were analyzed by nondestructive analyses. Small fragments of 13 bricks were also selected as sample bricks to be investigated by mineralogical and geochemical analyses, and the results were compared with nondestructive analyses.

The measurements of magnetic susceptibility, ultrasonic velocity, X-ray radiography and water absorption
were performed as a nondestructive analysis, while mineralogical and geochemical methods including X-ray diffraction, X-ray fluorescence, induced-coupled plasma mass spectroscopy and neutron activation analysis were performed by small-quantity-samplings from the bricks. Through these examinations, this study determined the provenance, production techniques and firing temperature of bricks from the royal tomb of King Muryeong.

![Figure 1](image1.png)

**Figure 1.** Location, appearance of the royal tomb of King Muryeong which made of bricks, Gongju, Korea.

### 3. Results and discussion

#### 3.1. Results from nondestructive analyses

The brick samples showed the magnetic susceptibility of 0 to $4 \times 10^{-3}$ SI unit and most of them concentrated on the 0 to $1 \times 10^{-3}$ SI unit showing the similarity of raw materials of brick samples (Figure 2). Although it is known that the magnetic susceptibility increases when the firing temperature of soil rises, the bricks made of soil with low Fe content keep the increasing range of magnetic susceptibility very low. Consequently, it is possible to determine the similarity of raw materials of brick samples by the magnetic susceptibility values.

![Figure 2](image2.png)

**Figure 2.** The results of magnetic susceptibility and ultrasonic velocity of the brick samples.

The water absorption of the brick samples ranged widely from 1.18 to 16.30%. The samples could be classified into a group with low water absorption of 1 to 6% and a group with high water absorption of 13 to 16%. The water absorption is a major factor that can be used to estimate the density and firing temperature of bricks. Specimens kneaded with similar soil to the brick samples were fired in different temperature from 500 through 1,200 $^\circ$C and the fire temperature and water absorption of the specimens were measured on every 100 $^\circ$C. The results were plotted and compared with that of the brick samples (Figure 3).
The plot indicated that most of the brick samples were fired at between 1,000 and 1,200°C. The firing temperature based on the water absorption concentrated between 1,000 and 1,100°C and near 1,200°C. In addition, the strength of the brick samples was determined by measuring ultrasonic velocity which detects cracks and weathering. Measured ultrasonic velocity values are distributed between 2,000 and 5,500m/s and were most of them at the 3,500-4000m/s range (Figure 2). As a result, it is assumed that most of the brick samples were fired in high temperature and has high strength. Although some brick samples have extra high strength showing 5,000m/s on the ultrasonic velocity measurement, most of the brick samples have weathering degree (k) of 0.2 to 0.4 (slightly weathered and moderately weathered, according to Ilev’s weathering grade (1967)). The result proved that the bricks have high durability and strength level. Consequently, the bricks from royal tomb of King Muryeong appear to be made with the refined material of the soil and fired at a high temperature. Although the ultrasonic velocity can change slightly due to the centuries of weathering, it is possible to estimate the firing temperature by water absorption and ultrasonic velocity measurement, both of which are nondestructive analyses. Ultrasonic velocity is in inverse proportion to water absorption and the measured values of the brick samples can be divided into two groups; samples with high firing temperature and samples with low firing temperature (Figure 4). Ultrasonic velocity is used to measure the density of the brick’s mineral structure and high ultrasonic velocity value indicates even alignment of the mineral crystals and high firing temperature.

Bricks from the royal tomb of King Muryeong have various patterns stamped on the side. Mostly lotus flower patterns are stamped and inscriptions are stamped in some cases. The size of the bricks is approximately 30-33mm in height and 14-16mm in width and it seems that number of molds with different patterns was used to manufacture various pattern-stamped bricks. X-ray radiography images of the bricks imply that the patterns were created by pressing patterned mold on the side (Figure 5). In other words, bricks with same pattern were manufactured by the same mold and after stuffing clay in the mold, the pattern side mold was pressed with high pressure to get a clear image of the patterns.

3.2. Results from mineralogical and geochemical analysis

Although nondestructive analysis is principle method for investigating the historical objects, results from nondestructive analysis have lack of the accuracy and quantifiable interpretations. In this study, small amount of samples were selected and analyzed by methodologies used in mineralogy and geochemistry to compare the results analyzed from nondestructive analyses.
As a result of mineralogical analysis, most of the bricks were mainly composed of quartz, plagioclase, and alkali feldspar. However, chlorite and kaolinite were found on the bricks fired in a low temperature or adobe brick, and hercynite, mullite, and even cordierite were found on the bricks fired in a high temperature. Most of the bricks were produced in a reduction firing atmosphere and bricks samples were fired at a temperature of 1,000 to 1,200 °C in the basis of their mineral phase. It is similar to the results by nondestructive analysis. It is assumed that the bricks including kaolinite and chlorite were not fired, and the bricks including cordierite and mullite were fired at high temperature over 1,200 °C.

As a result of major element analysis, the content of SiO₂, Al₂O₃, and Fe₂O₃ was 57~68wt.%, 18~22wt.%, and 4~7wt.% in order and did not show significant differences between each bricks. Showing lower SiO₂ content than that of source soil, it can be assumed that the macrocrystalline quartz components were separated out from the soil at the manufacturing process. Analyzing trace elements and rare earth elements in the brick samples and soil samples, it is indicated that the soil weathered from the same source rock was used for brick manufacturing.

![Figure 5. Radiographic images of bricks showing that light parts of images (arrows) in the corners. It means that clay was filled in the pattern of the cast and pressure was put on it in the process of brickmaking. (A, B) Brick samples (C) Conceptional cast image.](image)

4. Conclusion

In this study, material properties, firing temperature, difference in provenance of the bricks from the royal tomb of King Muryeong were investigated. The bricks were manufactured using macrocrystalline quartz eliminated soil which was weathered from the same source rock and fired at high temperature of 1,000 to 1,200 °C showing considerably high strength and low water absorption. Molds that has pattern on the side were used to manufacture patterned bricks. In case of analyzing historical objects which have difficulty in destructive sampling, nondestructive analysis can provide data on strength, materials properties, approximate firing temperature, and production technique of the historical bricks. In addition to the data, mineral and geochemical analysis can provide the quantitative interpretation of the bricks.

References


The Combination of Stone and Earth to Produce Earthquake-Resistant Constructions in the Peruvian Pre-Columbian Era

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Abstract

The immense architectural heritage of Peru was built with stones and earth, the two most accessible natural materials, with which humanity has built the oldest historical building sand higher cultural value. Variations of stone masonry with mud mortar have been developed in Peru, where their ancient builders investigated (based on trial and error) different ways to connect and combine the stones, looking for earthquake resistant stability through design criteria based on the strength, the stability and the performance, as in the modern world. Engineers at the Catholic University of Peru carried out 40 years of experimental studies on how to strengthen earthen houses, and for 30 years studies on how to conserve heritage buildings with different construction techniques of stone and earth. Recent studies of two archaeological sites, the oldest (Caral, 3000 B.C.) and the modern (Machu Picchu, 1500 A.D.), reveal common concepts of stable core pyramids, by controlling the relative displacement between the stones, through the use of mud mortars and mechanical methods such as vegetal thin ropes and bags. Regarding mud mortars, it has been discovered that the balanced clay-coarse sand is the most efficient way of giving better cohesive properties and dry strength. On the other hand, the use of rope bags provides stability to the stone massive volumes, and also allows developing systems that isolate buildings foundation, and dissipate seismic energy. This paper presents two case studies of declared World Heritage sites, to explain how these seismic stability problems were solved, how to preserve their cultural value and mainly to inspire future conservation solutions in stone buildings.

Keywords: Stone-earth, Stone masonry, Architectural heritage, Earthquake behavior

1. Introduction

Earth and stone are the earliest construction materials used in history due to its availability. With these materials, the most ancient and valuable historical sites were built. Early in time, men discovered that clay soils could be kneaded with water that after drying, acquire resistance. This helped constructors to build walls, shelter, and then erect public buildings.

Stone walls with dry joints, earthen walls, combination of earth and stone masonry walls, as well as earthen walls protected by stones were built based on the availability of the materials, the constructors’ preferences and the weather. Stone masonry with mud mortar consists of a technique with different characteristics, in which the earth plays the role of a connector material placed between stone units or the protected structure. In addition, the use of organic material (wood, bamboo, leather, vegetable fibers) was an important aspect of this technique.

Weather and ecological diversity were some factors that led to the development of different combinations with earth, stone and organic materials that fit suitably to the response of natural phenomena or disasters such as heavy rain, floods, storms, earthquakes, and landslide. The need of shelter required including new forms of walls, roofs or vaults that were perfected by means of trial and error. Subsequently, politics and religion empowered leaders and elites who created social sites and public buildings that required new techniques and intensive labor.

2. Peruvian historical experience

Studies in recent archaeological findings have allowed the rewrite of the Peruvian and American history for the last 20 years. The revealing of buried secrets has been so important that both, Peruvian and American history,
do not deeply know their origins or the level of scientific knowledge hidden underneath. Peru is one of the most seismic countries located in the Pacific Ocean and it is whipped by the effect of the El Niño-Southern Oscillation (ENSO) phenomena. This perverse combination of natural phenomena produced discontinuities in the history of the cultures and occupation of cities, shrines and public buildings. The formation of the Andean culture is linked to natural disasters and social conflicts such as sequel to survival (S. Hsiang et al., 2011), facing starvation, epidemics and abuses of theocratic elites. There was not a culture that exceeded 500 years without leaving their buildings. Certain ceremonial centers lasted about 1000 years (J. Vargas, 2012).

3. Caral Culture

It was created 50 centuries ago (3000 B.C.) and is the most ancient culture in America. This culture reveals valuable constructive knowledge that faced natural disasters. Studies in one of the most representative pyramids showed that constructors developed combinations made of earth, stone and organic materials that performed properly under disasters (Vargas J. et al 2011). See Figure 1.

![Galery Pyramid. Caral (3000 B.C.). Credit: Christopher Kleihege.](image)

In Caral, public edifications were built with different techniques made of stone, mud and organic materials in a hypothetical sequence that can be summarized in the following four steps:

- Stepped pyramids made of big stones fill in with rounded river stones, mud and sand. They succumbed against floods and earthquakes (aerial photos show the amphitheater, cut off by severe flooding).
- Stepped pyramids made of rounded river stone fill, without mud, sand, contained by stone façades with earthen mortar. They succumbed against earthquakes.
- Stepped pyramids with angular quarry stones fill, contained in stone façades with mud mortar. Even though they present a more stable behavior, there no evidence of improvement when succumbing against earthquakes.
- Stepped pyramids with stone cores made of wrapped by nets or bags, known as shicras, made of vegetable fibers, protecting the stone masonry walls that form the façades. The cores have lasted until current days by the repair of the façades after every earthquake.
In this last solution, constructors replaced clay mud to attach stones by strong plant braided ropes used as bags (brought from the high of the Andes). This solution, which is considered as an advanced engineering technique, became a precursor the current disseminated gabions. The cores of the pyramids are static and dynamically stable as it has been proven in the past. Figure 2 shows this solution that has withstood UV rays exposure. As it is stated in H. Fukuyama et al, 2012, studies in Japan using shaking tables evidenced that the layers of stone bags whose height varies from 0.1 m to 0.5 m are able to perform as seismic energy isolators and dissipators, when placed underneath a construction.

Figure 2. Core of stable pyramids made of loosen angular quarry stones pocketed with natural ropes. Galery pyramid, Caral. Credit: J. Vargas-Neumann, C. Iwaki y A.Rubíños.

Caral culture also developed Quincha (vertical timbers, horizontal vegetable fibers covered with mud). This technique is based on ductile and flexible walls and it is still used nowadays. Finally, the implementation of straw and mud, used in lightweight roofs, was also a development of this culture. These developments are a clear example of seismic resistance tools.

Chavin de Huantar culture (1500 B.C.) developed stable cores for their pyramids. Due to the occurrence of earthquakes, the combination consisted of elongated stones or rustic quadratic section, placed in an alternated layers arranged in perpendicular direction. Anequally balanced mix made of clay mud and coarse sand was placed between the layers. This mixture presented a percentage combination similar to the one found as optimum in laboratory tests (Vargas J. et al 1986 a). The height of the stable cores is several times the one of the thick stone façades settled with mud. This demonstrate that they presented a better behavior under more severe earthquakes.

Chavin culture had a major influence from the Tiahuanaco culture (800 B.C.), the ones that built a sacred city with huge stones that made the use of mud mortars useless. According to the conquerors (16\textsuperscript{th}century), the constructors of Tiahuanaco taught the Incas stone carving and building without the usage of mud mortars. Cusco, Ollantaytambo and Machu Picchu (1450 A.D.) are the most representative stone and earthen cities.

4. Machu Picchu

In the sanctuary of Machu Picchu, the stable core is natural, and consists of the hill or the bedrock itself. Constructions were built around and over the rock from the hill. In this citadel, three different types of techniques for the construction of earthen or stone walls can be recognized. The earth control the stability (preventing the stone landslide), whereas the stone protects the walls from rain. There are also two other techniques that do not involve the use of earth.

- I. Stone masonry with earthen core and joints. Visible earthen joint façades. Most representative technique found in Machu Picchu (see Figure 3).
• II. Stone masonry with earthen cores. Façades do not show the core. They look like walls with dry joints (see Figure 4).
• III. Stone masonry with earthen joints. Façades without showing earthen joints (see Figure 5).
• IV. Stone masonry with dry joints without soil (see Figure 6).
• V. Monolithic structures without joints (see Figure 7).

The citadel represents a display of free design combination with stone and earthen techniques.

*Figure 3.* Walls with cores and visible earthen joints, covered with stones. Credit J. Vargas-Neumann.

*Figure 4.* To the left, stone façades that cover earthen masses or cores. To the right, an upper view of the façade. Credit: J. Vargas-Neumann.

*Figure 5.* Stone walls with exposing earth from the inside. Credit: J. Vargas-Neumann.

*Figure 6.* Stone walls finely craved used only in sacred places. Less stable walls were built during the occurrence of earthquakes. Credit: J. Vargas-Neumann.

*Figure 7.* Monolithic sculpted stone structures. Credit: J. Vargas-Neumann.
5. Important Aspects to Take Into Account for the Structural Intervention on Stone and Earthen Masonry

Once the geometry, materials and deterioration of the site are known, it is necessary to define the damage causes and the role of each material presents. In stone and earthen masonry, the more vulnerable material is the earth and that is why it defines the stability and the intervention works should focus on it. Stone suffer less structural deterioration.

In order to prevent the loss of global stability of the masonry; earth (its components, its combinations and its repair) will be studied as a vulnerable material. Earthen components used as construction materials are mainly clay, unique active and indispensable component that provides strength, and inert components such as silt, coarse and fine sand. The latter is the one that best balances the cracks originated by drying shrinkage on the clay. In practice, the more resistant and cohesive earth is the one that presents the best combination of clay and coarse sand. When reinforcing earthen elements, previous studies on the components and the presence of clay as well as its proportion with straw are required.

The replacement of earthen materials when reinforcing, which is indispensable in seismic areas (The Lima Declaration for Disaster Risk Management of Cultural Heritage, 2010), should take place only if it is necessary by using clay soil balanced with coarse sand in an optimum proportion according to the tests performed on site. Many times the earth has been mixed with straw, which was proven to be the most efficient natural additive that controls cracking. In this case, the quality, size and percentage of the straw according to the earth are retained (Vargas et al. 1986). Instead of straw, animal hair (llamas, horses, rabbits) was also used.

It is possible to control the drying rate

![Figure 8](image_url)

**Figure 8.** Green line represents the usual mortar drying process, where the sun, winds and thirsty dry adobe blocks accelerate it. Blue line represents the drying rate retardant methods behavior, associated with less or no micro-cracks, better adobe-mortar adhesion and strength increase. Credit: J. Vargas-Neumann.
It has been evidenced in laboratory tests that in the past, mixtures of mud, drying rate retardant substances to avoid cracks, such as cactus mucilage (Opuntia Ficus Indica), manure or egg white, have been used (Vargas et al. 1986). It is convenient to prove the existence of these products. Delaying the drying rate of the mixture slows the acting stresses in the mud, the ones that are originated due to two factors: lacking of uniformity in moisture loss in the mud (the outside dries faster than the inside), and friction restrictions on edges or supports (outside parts again).

Simultaneously, the mud resistance has been uniformly increasing until reaching its dry strength, rapidly and without restrictions, and, consequently, avoiding cracking. The resistance increase rate is greater than the one of the acting forces in the mud. The graphic in Figure 8, shows how it is possible to use drying rate retardant methods to avoid or decrease cracking. To soak adobes just before putting them over the wet mortar during building a masonry wall, is a new good method, and the use of cactus mucilage instead of water is an historic one. These methods delay initial water evaporation process or drying speed from the initial normalized water content (100 %), until the permanent average rate which depends of weather and local conditions.

6. Conclusions

By oral tradition, since no writing is known about the Pre-Colombian Peru, public edifications were built based on pyramids, with stable and seismic resistant cores using different techniques, which should be studied in detail in order to guarantee secure and appropriate patrimonial interventions. The current knowledge regarding the use of the earth components is astonishing. Specially the balance between clay and straw or coarse sand. There is the need of spreading this knowledge for restoration works since it allows the controlling of cracks, improvement of cohesion and resistance. Stone-earth adherence is a function from the same knowledge.

It is necessary to integrate the work of ISCS, ISCEAH, ISCARSAH experts to guarantee the durability problems solution, stability and reinforcement of stone-masonry, in seismic and non seismic areas. The interdisciplinary teams, will bring new points of view, is not an addition, it is a multiplication effect. There are immense stock of cultural stone and earthen constructions, the oldest, most accessible and vulnerable. Innovative solutions are required, for each case and mixed techniques.

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Numerical Approach Using a FEM Software for Reproducing Diagonal Compression Tests on Stone Walls

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Abstract
Stone masonry is one of the oldest type of construction in the world due to the natural availability of stones and the ease of construction. This construction typology is characterized by brittle behaviour, the masonry has acceptable compression strength but low shear and tensile strengths; therefore, collapses and casualties are frequent due to earthquake loading. Recently, some researchers have performed experimental tests to improve the knowledge regarding stone masonry. However, there is still the necessity to develop numerical models able to reproduce the seismic behaviour. In this work a numerical approach to model a diagonal compression test of a rubble stone masonry is proposed within the finite element method. Since the mortar is the most important parameter in the seismic behaviour of stone walls, the procedure here represents the stone units as rigid bodies and the mortar as nonlinear plastic material with compressive and tensile degradation. This assumption allows the reduction of the degrees of freedom in the numerical model. The model is implemented in a commercial finite element software and is intended to simulate an experimental test performed in Italy. This approach is computationally efficient and can be easily extended to real buildings.

Keywords: Stone masonry, Numerical approach, Diagonal compression tests, Finite element method

1. Introduction
Stone masonry is one of the oldest materials used for construction around the world. In Europe, for example, ancient Greeks and Romans used stone as decorative or structural elements. The Greeks used stone basically as ornamental material and to build temples. The Romans with pozzolana mortar as binder material were able to build aqueducts, bridges, public buildings and many historical constructions as the Coliseum. In the Middle Ages stone material was not considered just as ornamental material, but was used to build complex shapes such as arches, domes etc.

The stone masonry can be broadly classified according to the unit shapes: rubble masonry (course rubble, uncoursed rubble, random rubble, dry rubble, polygonal rubble, flint rubble) and ashlar masonry (ashlar fine, ashlar rough tooled, ashlar rock or quarry faced, ashlar chamfered, ashlar block-in course). Looking at the typical Italian constructions, Carbonara (1996) and Mazzon (2010) classified stone masonry according to the mortar used and the shape of the stone units: masonry with blocks with regular shape (ashlar masonry); masonry with blocks with irregular shape (rubble masonry); dry masonry; and regular blocks with mortar. Besides that, looking at the wall thickness the stone wall can be composed on one single-leaf or multiple-leafs, with and without interlocking. One of the most common wall typologies appearing in old structures is the multi-leaves stone masonry, and its behaviour has been studied experimentally (Pappas 2012). Recently, some researchers have studied the dynamic behaviour of stone walls numerically, using finite element and discrete methods. However, due to the uncertainties related to the mechanical properties of stone walls constituents (especially the binder material), the numerical analyses still remains a difficult issue for the scientific community.

In this work a new methodology useful to study the dynamic behaviour of the stone masonry wall is proposed. In this paper the methodology is particularly applied to reproduce a diagonal compression test of rubble stone single leaf wall. The stones are treated as rigid body elements with three degrees of freedom (DOF)
while the mortar is treated within the plasticity theory, in particular using the concrete damaged plasticity model implemented in Abaqus 6.9 SIMULIA (2009). This model considers the compression and tension behaviour of the mortar as well as the damage parameters in order to reproduce the degradation due to reversal loads. This methodology is computationally efficient and allows the modelling of real structure with great accuracy.

2. Structural behaviour of stone walls

The structural behaviour of stone masonry depends on its geometry, on the type of texture (one leaf, double leaf, with or without mortar, connection between the leaves, filling voids), on the mechanical properties of its components (especially on the mortar) and on the mechanical properties of the composite. Especially in Europe, stone walls are built with multiple leaves, which means double or three-leaf walls. In the last case, the filling material that forms the inner leaf is composed with a very heterogeneous material which consists of mortar (sometimes mud), small rubble stones and other loose materials. The characteristics of the mortar, its thickness, and its compressive, tensile and shear strengths strongly influence the behaviour of the walls, while the stones behave almost as elastic elements. According to Valluzzi et al. (2001), the causes of the main structural problems of multi-leaf walls are the weakness of the internal layer, the deterioration of the mortar in the external joints and lack of connection among the leaves. The composite behaviour between the inner leaf and outer leaves is almost null when the walls are subjected to horizontal movement.

Stone masonry - as part of the unreinforced masonry typology - has a brittle behaviour during seismic actions. In-plane actions deteriorate the walls due to the combination of vertical and horizontal stresses, breaking the mortar because the low tensile strength is exceeded. The typical failure pattern is the X-shape in the wall plane. Then, the deteriorated walls are more vulnerable to out-of-plane loading, which can end with the detachment of the external leaves or the complete collapse of the wall by a combination of vertical and horizontal out-of-plane loads. Unfortunately, every time an earthquake comes this brittle behaviour ends with the collapse of dwellings, and with many human and economical losses. Some examples of this situation were seen in India during the 1993 Maharashtra earthquake (Mw 6.4, around 8 000 deaths) and 2001 Bhuj earthquake (Mw 7.7, around 13 800 deaths), and in Pakistan during the 2005 Kashmir earthquake (Mw 7.6, around 86 000 deaths).

3. Experimental program

In general, the principal objective of any experimental program conducted on stone masonry is the identification of the mechanical properties that represent the compressional, tensional and shear characteristics of the constituents. These mechanical properties are expressed through the constitutive laws which include the elastic and inelastic parts. Furthermore, the structural capacity of the composite stone walls can be studied with pseudo static monotonic and cyclic tests, while a complete behaviour of stone constructions can be identified with dynamic tests on real or reduced scale modules. For the purpose of this research, a diagonal compression test performed in the TREMA project (Technologies for the Reduction of Seismic Effects on Architectural Manufactures, Dolce et al. 2008) is used here to calibrate the numerical model. Within the scope of TREMA, some experimental tests on irregular tuff masonry with limestone mortar were performed at the University of Basilicata. These tests consisted on the mechanical characterization of the mortar and stone units, evaluation of the tensile and shear strengths of the stone walls through 3 diagonal compression tests (named M1, M2 and M3 and dimensions of 900 x 900 x 250 mm each wall, Figure 1) and the analysis of the seismic behaviour of two 2:3 scaled stone buildings (plan dimension of 3000 x 3500 mm, total high of 4200 mm). From the compression tests performed on the mortar, a mean value of 0.71 MPa with a COV of 0.22 was obtained. This strength value was kept as low as possible to reproduce the deteriorated stage of the mortar, typically found in historical stone masonry (Magenes et al. 2010). Prior to the application of the vertical load, a pre-compression load of 0.10, 0.15 and 0.20 MPa was applied to two opposite edges of M1, M2 and M3, respectively (Figure 1c), and maintained constant during the test. Then, the vertical load was applied within a force-controlled procedure until the collapse of the wall characterized by diagonal cracking and crushing at the head wall.
4. Finite element modelling: damage model for quasi brittle materials

Masonry is a composite material made of bricks and mortar joints, where each of the constituents has its own material properties, for this reason the behaviour is quite complex to model (Mazzon 2010). The finite element method (FEM) using calibrated stress-strain relationships represents a suitable numerical approach to reproduce the masonry behaviour (Tarque et al. 2013). The level of accuracy in the numerical models strongly depends on the knowledge of the material properties, on the type of analyses (linear, nonlinear), on the element used (shell, solid), and on the solution scheme adopted.

Previous research results have shown that the response of masonry structures up to failure can be successfully modelled using techniques applied to concrete mechanics within the FEM (Pelà et al. 2013). According to Lourenço (1996), the numerical modelling of masonry walls can generally follow either the micro-modelling of each of its components (discontinuous or discrete approach) or the macro-modelling of the wall (continuum approach), thus assuming that the masonry wall is homogeneous.

In this work the commercial software Abaqus/Standard has been selected to reproduce the approach proposed in this work. Since the stones are stiffer and much stronger than the mortar, the stones were modelled as rigid body elements. As it is known, rigid bodies have just 3 DOF, this assumption allows the reduction of a great quantity of degree of freedoms (DOF) when modelling big structures. The mortar was modelled considering a plastic-damage model developed by Lubliner et al. (1989) and later improved by Lee and Fenves (1998).

Figure 1. Experimental test performed by TREMA. A: diagonal compression test, B: scheme of the test (adapted from http://www.unibas.it/trerem/TRE-REMDW/).

Figure 2. Constitutive laws used by the plastic-damage model in Abaqus/Standard (modified from Wawrzynek and Cincio 2005). A: Tension behaviour, B: Compression behaviour.
This model is a continuum, plastic-based, damage model for brittle material, where the two main failure mechanisms are tensile cracking and compressive crushing of the material. This model assumes that failure of mortar can be effectively modelled using its uniaxial tension, uniaxial compression and plasticity characteristics (Figure 2). The strength degradation in the damage-plastic based model is represented by the damage factors \((dt, dc)\) that reduce the elasticity module in tension and compression for reversal loads. The tension and compression constitutive laws are the principal input data, as well as the fracture energy for each of them. The fracture energy represents the inelastic area below the stress-strain diagram divided by the element characteristic length, \(h\). This last value is used to avoid mesh dependency in the results (e.g. Lourenço 1996), and is the length of a line across an element for a first-order element; or half of the same typical length for a second-order element.

5. Numerical model: diagonal compression test

5.1. Description of the model

The geometry of the test modelled is shown in Figure 3A. Steel elements were placed at the base, at the top, and at two edges of the masonry wall (see dark lines in Figure 3A), the stones were represented by rigid body elements and the mortar by continuum elements. For the mesh, 4-node rectangular shell elements and 3-node triangular elements were used to represent the stone and mortar, respectively (Figure 3B). The characteristic element length was kept as close as possible to 21 mm for the mortar. The steel and stones were assumed as elastic and isotropic materials (Table 1). For the mortar, the module of elasticity \(E\), the Poisson's ratio \(v\), the specific weight \(\gamma_m\), and the compression strength \(f_c\) were kept as close as the ones reported by the experimental tests. The other material properties given in Table 2 were calibrated to match the experimental Force-Displacement curve with the numerical response and the numerical failure pattern. A dilation angle of 25 was considered for the analysis. The tensional softening curve for the mortar followed an exponential shape (Figure 2A) and the compressional hardening/softening curve followed a parabolic shape (Figure 2B), the equations to draw these curves can be seen in Lourenço (1996).

![Figure 3. A: Sketch of the diagonal compression test, B: Mesh of the numerical model.](image)

| Table 1. Elastic material properties for the steel, stone and mortar. |
|------------------|------------------|------------------|------------------|
| Steel            | Stone            | Mortar           |
| \(E\) (MPa)      | \(E\) (MPa)      | \(E\) (MPa)      |
| \(v\)            | \(v\)            | \(v\)            |
| \(\gamma_m\) (N/mm\(^3\)) | \(\gamma_m\) (N/mm\(^3\)) | \(\gamma_m\) (N/mm\(^3\)) |
| 200000           | 50000            | 950             |
| 0.25             | 0.25             | 0.26            |
| ---              | 16.7 E-06        | 16.0 E-06       |

| Table 2. Mortar material properties used for the plasticity-damage model. |
|------------------|------------------|------------------|------------------|
| Tension (softening) | Compression (hardening/softening) |
| \(f_t\) (N/mm\(^2\)) | \(f_c\) (N/mm\(^2\)) | \(G_t\) (N/mm) | \(G_c\) (N/mm) | \(\varepsilon_p\) (mm/mm) |
| 0.04             | 0.001            | 0.50            | 0.10            | 0.294            | 0.004            |
5.2. Numerical analysis

For the analysis the sequence of loading was equal as in the experimental test: A) boundary conditions were specified at the wall base, B) the pre-compressional load was applied at the two edges and kept constant, C) the last step considered an application of a vertical load at the wall top until failure. Due to the rigid body concept, the constraints at the base and at the wall top were directly applied to the centre of gravity (C.G.) of the low and top stone, respectively. The top load followed the nodal rotation of the C.G. and the geometrical effects were considered in all the models. Besides, the analysis considered a full Newton-Raphson iterative procedure and an automatic stabilization was selected for the convergence criterion, with a specified dissipated energy fraction of 0.0001 and an adaptive stabilization with maximum ratio of stabilization to strain energy of 0.05. These values were selected to obtain reasonable failure pattern in the model without loss of accuracy.

5.3. Numerical results

The numerical model reproduced fairly well the general response, the stress distribution and the failure pattern of the experimental test. In the Force-Displacement curves (F-D), shown in Figure 4, the reaction due to gravity loads was not considered, so the contribution to the vertical force was just due to the pre-compressional and vertical load. The assumption of rigid body elements for the stones seems to be acceptable to represent the structural response.

![Figure 4. Comparison of the experimental and numerical Force-Displacement curve and evolution of damage during the diagonal compression test.](image)

It is important to note that the first part of the curve is controlled by the module of elasticity of the mortar which was calibrated with a parametric analysis. When the stresses exceed the maximum tensile strength defined in Table 2 some cracking appears changing the slope of the F-D curve. At 0.30 mm displacement, some crushing was observed at the top of the wall due to compressional stress concentration at the mortar. As the vertical load increased, more diffuse cracking appeared in the mortar. At 0.50 mm top displacement 3 diagonal cracking paths through the masonry wall started to form. In the experimental test these diagonal quasi-vertical cracking separated the wall into almost three parts (see Figure 1B). In the numerical model, the compressional stress at the central wall part increased and more crushing was likely to occur until the no convergence of the model, which meant the wall failure. It is important to mention that in other tests where there is not pre-compressional load, the cracking is almost single and parallel to the vertical top load, dividing the wall into two parts.
So, in the F-D curve 3 zones were identified. The first, which is the elastic, was controlled by the elastic modulus of the mortar. Then, the mortar tensile strength controlled the slope change of the F-D curve and the tensile fracture energy allowed the stress re-distribution. Finally, the compressional stress concentration at the top part of the wall defined the maximum vertical force and the wall collapse.

6. Conclusions

A methodology to numerically reproduce a diagonal compression test on a stone masonry is proposed here. The efficiency of this methodology is related that the stones are much stiffer and stronger than the mortar, and this last has a great influence in the global wall response. Since the stone units response almost elastically, they are modelled as elastic rigid bodies; however, the mortar is modelled with a plastic-damage material with tensional and compressional degradation. This plastic model is implemented in the FEM software Abaqus 6.9 SIMULIA (2009). In this paper the material properties of the mortar were calibrated based on experimental and literature information to match the experimental results of the diagonal compression test. It was observed that both tension and compression mortar strength are the two most important parameters to calibrate to obtain a good correlation with the experimental results. The good agreement between the numerical and experimental test shows that the methodology proposed is very promising. The method is efficient computationally and can be easily extended to study large and complex structures.

References

Similarities and Differences in Evaluation Methods for Stone or Earthen Surfaces

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Abstract

To prevent or repair from natural and anthropogenic weathering, protective layers can be applied to improve hardness of stones and earthen surfaces, to increase their internal cohesion or to prevent them from important water penetration. Earthen surfaces are often considered as hardly measurable and references and guidelines to evaluate treatments rarely exist. In the frame of a national research project financed by the French ministry of culture, earthen surfaces have been stabilized with two biopolymers, linen oil and flour glue. A panel of lab and field methods has been applied to evaluate their efficiency as a protective layer, compatibility with un-treated material, and durability faced to natural weathering. From high-technology methods as surface roughness measurements to the easiest field tests of contact sponge and tape test, we will show that the two stabilized earthen surfaces can be distinguished and their main properties can be underlined. Stone and earthen surfaces can be studied following equivalent protocol and many of the stones methods can be transposed or slightly modified to evaluate earthen surfaces.

Keywords: Evaluation, Methods, Stone, Earthen surfaces

1. Introduction

For many years, the field of stone conservation has developed and improved treatments to consolidate internal cohesion of porous media or to innovate in new water repellent product. The field of historical monuments has been surrounded by chemical products and is still nowadays an area of innovation for chemical firms. Thus, architects and conservators in charge of historical monuments have urgently required some tools to better know the needs of the monuments to evaluate the specific needs surrounded application of a conservation product. Terms of efficiency of products, compatibility with old surface, durability have emerged and with those the corresponding methods to satisfied those new exigencies. In 1997, Sasse and Snethlage wrote methods for the evaluation of stone conservation treatments (Sasse and Snethlage, 1997, p.227). Those methods gave some clues and requirements to evaluate cleaning or hydrophobic treatments, repair mortars or coatings on stones. Those requirements have been largely diffused through Europe, Germany and France in particular, and through a review made by the research laboratory of historical monuments (LRMH) on consolidation and hydrophobic treatments applied on stone monuments (Bromblet et al., 2002). More recently a review paper describes these criteria for selection and evaluation of products for the stone conservation (Tabasso and Simon, 2006).

Earthen construction is poor in such references and guidelines to evaluate treatments rarely exist. The main reason of this gap is the justified mistrust of earthen conservators towards chemical treatments. Because of a lack of evaluation methods and requirements, most of decision makers or scientist will prefer to not intervene or as less as possible, protecting the building or the site with external tools as shelters or capping for instance. Actually those will always be a solution to consider. But others ways are possible and need to be investigated as the use of bio-polymers. They are traditionally used in earthen material as the albumin of white egg or cellulose fibers decoction and have proved their hydrophobic or strengthenereffects on earthen surfaces (Fontaine et al., 2008; Fontaine et al., 2009; Joffroy, 2006).
2. The specific requirements of earthen surfaces

A protective layer on earthen surfaces can be applied in two different ways. It can be under a liquid form and be sprayed or brushed on the surface, or it can also be as a mud plaster already containing the active compounds. The first way involves that the applied layer should penetrate into the substrate, the second way that the plaster should be easy to apply and adhere to the substrate. In this aspect, a protective layer on earthen material should protect the substrate from rainfall and erosion, improving the resistance to liquid water penetration as well as the resistance to abrasion, it should be easy to apply and with either a good penetration or a good adherence to the substrate. On the other hand, a protective layer should not stop water vapor permeability to allow the substrate to “breath” correctly, it should not change the aesthetic aspect of the surface, and it should not increase too much the surface strength in order to keep a good mechanical compatibility between both surfaces.

Surprisingly, earthen material is not so different than stone. The mineralogy composition can be very close to some sedimentary stone, for instance some clay reach sandstone, can present similar grain and pore size distribution than earthen material. The sedimentary process is less developed for earth than for the sandstone and the clay content can be very important which involve a great sensitivity to water either in liquid or vapor phase. For those reasons, methods to evaluate properties of earthen surfaces should prevent the material from a excess of water. For instance, methods to evaluate capillary or drying on stone are not really adapted to earthen material as sample are in direct contact or even immersed in liquid water. As well, grain size may be large and heterogeneous in earthen material. Mechanical tests as drilling resistance or bi-axial flexural strength consider small surfaces of measurements and are thus not relevant.

3. Sampling for suitable analysis

In the frame of any application and evaluation of a protective layer, samples have to be taken from the original substrate to determine its properties. To evaluate efficiency and moreover compatibility of the protective layer with old substrate it has to be applied on samples of the original substrate or on a substrate presenting the closest properties to the original one. To illustrate our research, molded earthen surfaces have been stabilized with two biopolymers, linen oil and flour glue, directly applied on the surface. The linen oil is a ready to use oil at first cold pressure, while the flour glue was homemade boiling three volumes of water for one volume of flour, then the paste is six times diluted to be fluid and applicable on a dry surface. Then, a panel of lab and field methods has been carried out to evaluate their efficiency as a protective layer, compatibility with un-treated material, and durability faced to natural weathering. Mineralogy of the earthen material will probably influence the effect of the biopolymers. In this study we considered a material containing 8% of clay minerals composed by 44% of kaolinite, 28% of chlorite and 28% of illite.

4. Evaluation of efficiency and compatibility of earthen surfaces

Before any protective layers to be applied, the substrate has to be identified and well characterized. The first requirement is then to determine the properties of the substrate in order to select the most compatible protective layer.

4.1. Aesthetics properties

A protective layer may change the aspect (color, roughness, brightness) of the surface. This esthetical aspect needs to be first evaluated and some tolerance limits can be determined through a dialogue with decision makers. Thus, taking pictures with a color chart are always an easy and fast way to appreciate the surface aspect. Color measurements using a colorimeter instrument will precisely measure the color variation and the brightness and can be equally measured in the lab and in situ. Visual aspect can also change through time and be influenced by UV or water exposition. It is always useful to well document any intervention at periodic interval. Color measurement is then a useful tool to evaluate durability of the surfaces in term of esthetical aspect.

The surface due to the application of the flour glue coating presents an homogeneous texture, covered by a bright layer on the top substrate (Figure 1). As it can be seen on a profile, the coating shows a low penetration
into the substrate with a thickness of the deposit film <10 µm. The coating seems to well adhere to the substrate but seems to create some micro cracks at the interface with the untreated material leading to some grains detachment. On the other hand, the linen oil coating shows a penetration around 4 mm (Figure 2). The surface is darker after the application but the coating is homogeneous.

4.2. Physical properties

Changes in physical properties reveal the effectiveness of the surface layer to better resist to water penetration. They also indicate the compatibility of the new protective layer with the older substrate in term of water vapor permeability. The contact sponge method was first developed at the CNT-Florence by Tiano and Pardini (2004) in the purpose to evaluate and monitored capillary of a protective layer in the laboratory as well as in the field. This low cost method has the advantage to not bring a large amount of water on the surface and for a short time of measurement (1 minute can be sufficient). It consists on pressing a wet sponge onto the surface with specific amount of water, time and pressure (Figure 3) (Ferreira et al., 2011; Vandervoode et al., 2009). Working conditions have to be adapted to earthen material, but the method has already proved its correlation with others capillary measurements the normative capillary rise measurement traditional carried out on stone evaluation surfaces (NF EN 15801, 2010). It is a relevant test to characterize effectiveness as well as durability of a surface through time and is totally adapted to earthen surfaces.

Each studied earthen surfaces have been six times measured before and after biopolymers application. In Table 1, results show that capillary coefficients are clearly reduced after the application of linen oil or flour glue on the top surface of the earthen material where values fall down below \(1 \text{ g.m}^{-2}.\text{s}^{-1}\). This evaluation method of the capillary suction, originally performed on stone surface, proves in a simple and reproducible way the efficiency of an applied treatment.

![Figure 1](image1.png) Application of flour glue on the earthen top surface; on the left hand side, cross section view and on the right hand side view of the top surface.

![Figure 2](image2.png) Application of linen oil on the earthen top surface, on the left hand side, cross section view showing a penetration depth around 4 mm and on the right hand side view of the top surface.
Water vapor permeability is valuable to evaluate the compatibility of the new protective surface with the older substrate. It consists in measuring the amount of water vapor crossing the material under a differential of atmospheric pressure (Figure 4). The µ-value represents the coefficient of resistance of the material to water vapor permeability. Indeed, stone requirements indicate that water vapor permeability can only vary in the range of 30% of the permeability of the substrate. Such requirements can be established for earthen surface allowing the water vapor flow to circulate. The norm NF EN 15803 (2010) for evaluation of water repellent applied on stone, can be also used for earthen material. Pre-conditioning of the earth sample at high humidity condition can be necessary for a slow drying and limited cracks of the sample disk. Presented results are calculated from an average of three disks measured over 200 hours and showing a linear regression such as $r^2 \geq 0.9992$ (Table 2).

Measurements of the µ-value show clearly the influence of the linen oil application on the earthen material, increasing its value of more than 50%, while the application of the flour glue seems to respect totally the water vapor permeability of the original surface (Table 2).

### 4.3. Mechanical properties

Mechanical properties are significant to determine resistance to abrasion, and adhesion of a protective plaster to the substrate, but also to evaluate strength compatibility between a protective surface layer and its substrate. Indeed, over-strengthening of a surface may induce mechanical stress at the interface surface/substrate and involve most of the time a detachment of the surface along the interface. Resistance to abrasion has been already adapted and well developed to earthen surface (séries technologies, 2000).

**Figure 3.** Measurements steps of the contact sponge methods test.

**Figure 4.** Measurement of water vapor permeability. a) theoretical drawing; b) application to earthen disks for a 10 cm cup diameter. 5 disks have been measured for each type of surface.

**Table 1.** Capillary coefficients measured on earthen surfaces. 5 measurements have been taken for each type of surface.

<table>
<thead>
<tr>
<th>Type of surfaces</th>
<th>Untreated Earthen surface</th>
<th>With linen oil application</th>
<th>With flour glue application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capillary coefficient (g.m$^{-2}$.s$^{-1}$)</td>
<td>$6.7 \pm 0.7$</td>
<td>$0.16 \pm 0.03$</td>
<td>$0.5 \pm 0.1$</td>
</tr>
</tbody>
</table>

**Table 2.** Results of the µ-value obtained on untreated earthen material, treated with linen oil and with flour glue.

<table>
<thead>
<tr>
<th>Type of surfaces</th>
<th>Untreated earthen surface</th>
<th>With linen oil application</th>
<th>With flour glue application</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ (-)</td>
<td>$9.1 \pm 1.2$</td>
<td>$14.6 \pm 2.2$</td>
<td>$9.7 \pm 2.6$</td>
</tr>
</tbody>
</table>
It consists in brushing with a metal brush at a constant pressure over a given number of cycles. A coefficient of abrasion can be calculated expressing the ratio of the surface to the quantity of the material removed by brushing. The coefficient can be then compared before and after the application of the protective layer and determine its efficiency against erosion. It also can help to evaluate durability of the layer taking measurements through a long period of time under environmental exposure.

Scotch tape test have been tested by Drdacky et al. (2011) to evaluate cohesion of decayed and consolidated stone surfaces. The test consists on measuring the detached material after the application of a double face scotch tape of 2cmx5cm for 90 s. Measurements is repeated five to ten times on the same area and reproduced three times on an equivalent surface. The obtained results may show a profile of the detached mass powder as a function of the number of scotch tape applied on the same area. Typical profile on decayed stone is may show a decrease of the amount of detached powder with the number of applied scotch tape on the same area, and thus reveals the most decayed layer of the stone. After a consolidation treatment, the series of scotch tape application may illustrate a decrease of the amount of detached powder from the stone surface.

For earthen surfaces, scotch tape test seems to show different results than for stones (Figure 5). Indeed, the obtained profile on the untreated earthen surface reveals an increase of the amount of detached powder with the number of applied scotch tape. The surface is then weaker with the abrasion induced by the tape application. However, the application of the linen oil on the earthen surface shows a relevant reduction of general susceptibility to abrasion. Detached mass powder is lower than for the untreated surface and the profile is almost linear. That is not the case with the application of the flour glue, which is removed with the application of the scotch tapes; it illustrates the low power of adhesion of this protective coating on the top surface of the earthen material.

5. Evaluation of durability of protective layer

Artificial weathering can be used to evaluate durability of the new protective layer. It has to consider the natural environment of the original substrate (UV, rain, frost exposure) and the adapted number of cycles. Main of the tests is carried out in climatic chambers where environmental conditions are controlled and monitored. Then, the different measurements carried out for the evaluation of efficiency should be re-measured and compared. However, artificial weathering gives indication on the way the material will decayed, but is not relevant for weathering processes in the natural environment (Sasse and Snethlage, 1997). The best way to evaluate durability remains long time exposure to natural environment changes (several years). Then, measurements after exposure can help to evaluate the evolution of the efficiency of the protective layer. For instance, capillarity measurements using the sponge test which can be used in the field, is a relevant method to monitored evolution of hydric properties of an exposed protective layer.

**Figure 5.** Profile of mass of detached powder as a function of scotch tapes application on the same area.
6. Conclusion

Linen oil forms a low permeable coating but an efficient protection against liquid water, increasing the durability of the earthen surface. Coating of flour glue seems to preserve the permeability properties of the original earthen surface but is present a poor durability faced to water flow. Penetration and adherence of the flour glue may be optimized by higher dilution rate and might be used as an indoor coating. Before applying a new protective layer on earthen surfaces, the first and main point to consider is its necessity and its function which is required in term of protection. Then it is essential to consider a general methodology for the evaluation of any new protective layer on earthen material. It can be divided in four interdependent steps.

Step 1: Visual site observations, condition mapping of the monument/environmental condition

Step 2: Efficiency & Compatibility tests (laboratory and field measurements) - determination of the substrate properties before and after application of the protective layer

Step 3: Durability – determination of the properties of the protective layer after adapted artificial weathering and after long term exposure to natural environment.

Step 4: On site monitoring.

Each steps of evaluation of earthen surfaces can be characterized by a measurement as it is usually carried out for evaluation of stone treatment. Using such methodology will reduce failures and incompatibility which have already occurred in the past.

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Characterization of Mortar in Historical Beylerbeyi Palace

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Abstract

Beylerbeyi Palace was built between 1861 and 1865 as a royal palace in Istanbul, Turkey. Having a masonry structural system the palace has some earthquake oriented damages. For this reason the structure is investigated. As the initial part, this study aims to characterize the mortar used in historical Beylerbeyi Palace and determine its mechanical properties. The chemical and mineralogical survey has been conducted over the mortar ruins from the original structure. Thin Section (TS), Scanning Electron Microscope (SEM), X-Ray Diffraction (XRD) and Energy Dispersive X-Ray (EDX) analyses have been applied. Mineralogical structure of the mortar has been determined and the mortar is classified as Khorasan type lime mortar used in Ottoman times. By using two different mortar formulas, test specimens are produced and tested after six month of production. Mechanical properties of mortar have been extracted from the obtained tests results by using European norms.

Keywords: Historical mortar, Characterization, Mechanical properties

1. Introduction

Every city in Turkey has many historical structures, built especially in Seljuk, Byzantine and Ottoman times. For the modern engineers and architects construction techniques of the old structures are always in importance with respect to both the lessons taken from them and conservation work to make them stronger against aging and earthquake effects. This study is grown up as the initial step of a broader one which aims to investigate the earthquake performance of Beylerbeyi Palace. In this paper, mortar properties of Beylerbeyi Palace have been investigated. Mortar identification is essential for several reasons, such as, determination of origin of the material, mechanical properties of the material, and determination of appropriate restoration materials. Before starting to elaborate the details of performed works, it would be valuable to summarize the history and general architectural features of the structure.

2. History and Architecture of the Structure

Beylerbeyi Palace is the largest and the most elegant Ottoman palace on the Asian shore of the Bosporus. It was constructed between 1861 and 1865. The palace was generally reserved for summer use by the sultans or to accommodate foreign heads of state visiting the Ottoman capital. The palace is shown in Figure 1.

The palace consists of two main floors and a basement. In the basement floor story heights vary between 1.5 m. and 2.2 m. whereas in regular floors, story heights change between 6 – 9 m. It has three entrances, six state rooms and 24 smaller rooms. The building has a 72 m length along the shore 48 m in the perpendicular direction (Aras, 2007).

The load bearing system is mainly made of masonry walls and timber slabs. The basement floor of the structure enables to identify the wall system which is composed of lime mortar, brick and stones. It is determined that the slab of the structure is mainly composed of two types of timber cross-sections. 20x20 cm² beams (supporting beam) were located on the masonry walls and 8x40 cm² beams (slab beam) with 40 cm spacing lie between two walls perpendicular to wall direction. The thickness of the walls in the first story is
generally 80 cm while it is 60 cm in the second floor. Cast iron clamps were used within the walls. The exterior face of the structure was covered by “küfeki” stone while interior faces were veneered with stucco and lime plaster and timber cover. Figure 2 shows wall details from the structure. A detailed damage survey was carried out in the palace. On the first and second floors of the structure several cracks were observed (Aras, 2010).

3. Mortar Identification

For the investigation of the earthquake performance of Beylerbeyi Palace, the state authorities did not give permission for material investigation. However a damage caused by the metal clamps placed within the masonry walls gave a good opportunity for mortar investigation. The oxidation of cast iron clamps used within the masonry caused swelling and finally cracking of the wall in a room and stair case in harem part. This damage ended up with the separation of about 50×50 cm² wall part in the room as seen in Figure 3. This damage enabled us to have original mortar ruins from the structure to have mineralogical and chemical survey.

Figure 1. Beylerbeyi Palace, Istanbul.

Figure 2. Structural wall details from the palace.
More recently developed mortar characterization schemes have optical microscopy as the first step in identifying the aggregates, of various mineral additions, binder type, and binder-related particles and in describing the pore structure. SEM analysis is, together with an XRD analysis, the most valuable second step in the characterization process of historic mortars. SEM analysis can be performed on mortar fragments or on polished epoxy-impregnated sections. With a SEM equipped with an EDX-detector, valuable information can be obtained on the mineral phase composition (Elsen, 2006). In that respect chemical and mineralogical composition of mortar from historic Beylerbeyi Palace was determined by Thin-Section analysis, Scanning Electron Microscope-Energy Dispersive X-ray (SEM-EDX) analysis and X-Ray Diffraction (XRD) analysis.

3.1. Thin sections under polarizing microscope

For the characterization of mortar, the study of thin sections under the polarizing microscope is an efficient analytical technique. A thin section is made by grinding down a slice of rock which has been glued to a glass slide until it reaches a thickness of about 0.03mm (30 microns). At this thickness most minerals become more or less transparent and can therefore be studied by a microscope using transmitted light. In this study five thin sections were investigated (Figure 4). By calculating the area covered by the components roughly, it was determined that, about 60% of the mortar is binding material and remaining part is the grains. These grains contain mineral particles, quartz particles and clearly identified brick powder particles. Table 1 summarizes the identified ingredients of the thin-sections.

Figure 3. Damage induced by the oxidation of metal clamps before and after the separation of wall segment.

Figure 4. Thin sections.
Table 1. Mortar ingredients according to thin-section analysis.

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Binding Material (%)</td>
</tr>
<tr>
<td>TS-1</td>
<td>50</td>
</tr>
<tr>
<td>TS-2</td>
<td>50</td>
</tr>
<tr>
<td>TS-3</td>
<td>60</td>
</tr>
<tr>
<td>TS-4</td>
<td>65</td>
</tr>
<tr>
<td>TS-5</td>
<td>67</td>
</tr>
<tr>
<td>Average</td>
<td>58.4</td>
</tr>
</tbody>
</table>

3.2. Scanning electron microscope views and energy dispersive x-ray analysis

A Scanning Electron Microscope (SEM) analysis is, together with an X-Ray analysis, the second step in the characterisation process. The mortar specimens were searched under Philips XL30ESEM-FEG&EDAX, Environmental Scanning Electron Microscope and Energy Dispersive X-Ray equipment. Two mortar specimens were investigated. Mineralogical structure of the ingredients of the mortar were tried to be identified with EDX. Good connection between particles and binding material was observed through the SEM views. No gap or cracks were determined. The general grain size varies between 50 μm and 1,200 μm for mortar.

The EDX analyses were performed simultaneously with the SEM. It was determined that the mineralogical origin of the particles is quartz, SiO$_2$. Figure 5 shows the SEM views and EDX analysis of particles. Wt % column shows the weight ratio of each element and oxides. Occasionally feldspar (Na, Al, K) minerals were seen through the EDX patterns of aggregates. P1 particle is obviously quartz particle while P2 particle is feldspar.

Figure 5. SEM views and EDX analysis of particles P1 and P2.

3.3. X-ray diffraction analysis

X-ray Diffraction (XRD) clarifies the nature of the mineralogical phases of the samples (Güleç and Tulun, 1997; Antonelli et al., 2002; Bianchini et al., 2004). Four pulverized mortar specimens different than those of used in previous methods were taken from aforementioned places in the palace and analyzed under Rigaku D/Max-Ultima+/PC XRD device by using Cu Kα radiation. XRD pattern verified that mortar is composed of calcite, quartz and feldspar elements. Mineral ratios were estimated by using line magnitudes and areas on the diffractogram. Table 2 summarizes identified component ratios for each specimen.

3.4. Result of the characterization process

When the findings of the employed methods are assessed, it is seen that there is a good agreement between the results. These three methods gave the mineralogical ingredients of the mortar as quartz, calcite and feldspar.
In two of recent studies, Boke et al. investigated the mortar of three historic bath buildings in Anatolia and Ipekoglu et al. investigated the lime mortar in madrasas, historical educational buildings, and they obtained the same mineralogical composition as that of Beylerbeyi Palace (Böke et al., 2006; İpekoğlu et al., 2007). Another study is directed by Regional Directorate of National Palaces and aims to characterize the mortar of Dolmabahce palace constructed in 1856 (Yüzer et al., 2000). With the varying ratios lime, fine sand, brick powder and marble powder were determined as the main components of the samples. A type of fibre was also seen in some samples. These studies classify the mortar as the general lime mortar named as Khorasan. This mortar was used in Byzantine, Seljuk and Ottoman. The binding material of this mortar is carbonated lime while as aggregate, river sand, pebbles, brick pieces and powder have been used together with hay, horse hair and goat hair which have served as fibres (Arioğlu and Acun, 2006). In the light of the performed mineralogical survey, recent studies and the historical information about the construction period of the structure, it can be concluded that the mortar of Beylerbeyi Palace is khorasan mortar.

**Table 2. Percentage of Calcite, Quartz and Feldspar for each specimen according to XRD analysis.**

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Mineralogical Components</th>
<th>Calcite (%)</th>
<th>Quartz (%)</th>
<th>Feldspar (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XRD-1</td>
<td></td>
<td>60</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>XRD-2</td>
<td></td>
<td>30</td>
<td>65</td>
<td>5</td>
</tr>
<tr>
<td>XRD-3</td>
<td></td>
<td>53</td>
<td>43</td>
<td>4</td>
</tr>
<tr>
<td>XRD-4</td>
<td></td>
<td>85</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>57</td>
<td>37</td>
<td>6</td>
</tr>
</tbody>
</table>

4. Laboratory testing of reproduced mortar specimens

Mechanical properties of mortar are the initial data for the behaviour and mechanical properties of masonry for Beylerbeyi Palace. Two different khorasan mortar formulas were used to produce the test specimens. In the first formula (F1), the mortar is the combination of slaked lime, brick powder and water (Table 3) (Akman et al., 1986). The second formula (F2) is used for the restoration works of the historical structures by Regional Directorate of National Palaces in Turkey (Aras, 2007). The mortar is the combination of slaked lime, brick powder, fine sand, fibre, and water (Table 4). The brick powder used in the specimens is obtained by pulverizing normal clay burnt bricks. In both F1 and F2 the maximum size of the grains is 2 mm.

**Table 3. Mixture proportions of the ingredients in F1.**

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Lime</th>
<th>Brick Powder</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion (by weight)</td>
<td>1.00</td>
<td>1.22</td>
<td>2.10</td>
</tr>
</tbody>
</table>

**Table 4. Mixture proportions of the ingredients in F2.**

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Lime</th>
<th>Brick Powder</th>
<th>Fine Sand</th>
<th>Water</th>
<th>Fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion (by volume)</td>
<td>4.00</td>
<td>4.00</td>
<td>2.00</td>
<td>1.50</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Before mixing the ingredients, lime slurry was formed by mixing the slaked lime and water and it was left to stand 24 hours. Then the brick powder and other ingredients were added to the mixture. The specimens were produced and tested according to TS EN 1015–11 (Turkish Standard Institution, 2000). Three-5cm×5cm×5cm cubic specimens and 4cm×4cm×16cm prismatic test specimens were created for each type of formula. After six-month curing, the tests were performed. Figure 6 illustrates the testing procedures and failed specimens.
Stress-strain diagrams were obtained for each specimen (Figure 7). Numerical values are listed in Table 5. At the failure point similar crack patterns were observed for both types of mortar specimens. The average compressive strength for both kind of mortar is roughly the same. On the other hand there is a clear difference in strain capacities. The average ultimate strain for F1 mortar is measured as 0.04 while that is 0.055 for F2 mortar. Secant modulus of elasticity for mortars was also determined as the slope of the line intersects the origin and one third of the maximum stress on stress-strain curve of each specimen.

Flexure tests were also performed to determine the flexural strength of the mortar. For each mortar type, three specimens were tested on three point flexure jig (Figure 6). The specimens exhibit brittle behaviour and via a single vertical crack, which occurred just beneath the application point of the load they failed. The determined mechanical properties for each test are summarized in Table 5. It should be noted that, mortar of F2 formula has a greater strain capacity and flexural strength while the modulus of elasticity is less than the mortar of F1. This may be the result of the addition of fibre to the mortar. This explains the reason of addition of hay or goat and horse hair to the mortar in the old times in Anatolia (Akman et al., 1986).
Table 5. Mechanical properties of laboratory made khorasan mortar specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Compressive Strength (MPa)</th>
<th>Strain at Maximum Stress</th>
<th>Ultimate Strain</th>
<th>Modulus of Elasticity (MPa)</th>
<th>Flexural Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1-1</td>
<td>4.37</td>
<td>0.019</td>
<td>0.041</td>
<td>902</td>
<td>1.86</td>
</tr>
<tr>
<td>F1-2</td>
<td>4.69</td>
<td>0.010</td>
<td>0.039</td>
<td>1,748</td>
<td>1.32</td>
</tr>
<tr>
<td>F1-3</td>
<td>4.55</td>
<td>0.011</td>
<td>0.041</td>
<td>730</td>
<td>1.53</td>
</tr>
<tr>
<td>F1 Ave.</td>
<td>4.54</td>
<td>0.013</td>
<td>0.040</td>
<td>1,127</td>
<td>1.57</td>
</tr>
<tr>
<td>F2-1</td>
<td>4.06</td>
<td>0.022</td>
<td>0.054</td>
<td>312</td>
<td>1.63</td>
</tr>
<tr>
<td>F2-2</td>
<td>5.59</td>
<td>0.025</td>
<td>0.064</td>
<td>508</td>
<td>1.79</td>
</tr>
<tr>
<td>F2-3</td>
<td>4.39</td>
<td>0.017</td>
<td>0.048</td>
<td>599</td>
<td>1.71</td>
</tr>
<tr>
<td>F2 Ave.</td>
<td>4.68</td>
<td>0.021</td>
<td>0.055</td>
<td>473</td>
<td>1.71</td>
</tr>
</tbody>
</table>

5. Conclusion

The mortar ruins taken from historical Beylerbeyi Palace have been investigated. Performed mineralogical and chemical analyses are in good agreement and they have revealed the components of the historic mortar as Calcite, Quarts and Feldspar elements. The mortar has been classified as khorasan mortar used in Ottoman time.

Mortar specimens have been produced in laboratory by using two different khorasan mortar formulas. Performed compression and flexure tests have given the mechanical properties such as compressive strength, flexure strength, young modulus, strain at maximum stress and ultimate strain values of the mortar. Although the compressive strength of the mortars is close to each other, F2 mortar has exhibited more ductile behaviour than F1 mortar. For the future restoration works, F2 mortar is more appropriate than F1 mortar. These characteristics are important and can be used for the future assessments and analyses related to the palace.

Acknowledgements

This work was developed within the FP6 research project, Protection of Historical Structures by Reversible Mixed Technologies (PROHITECH). The authors express sincere gratitude to Prof. Dr. Fahri Esenli and Orhan Yavuz, Yunus Aydin and Harun Yüksel brick factory.

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Introducing Petrography Methods, XRD Analysis and ISRM Standards in Technology of Stone used in Thresholds and Plinths of Achaemenid Palaces of Pasargadae

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Abstract

Pasargadae complex consists of some stone monuments built in 559 B.C. located far North West of Shiraz plain in Iran. There has been lots of erosion in the course of time in capitals, shafts and plinths of columns. There is a widely use of a special type of black stone in structural elements of Pasargadae which have had lots of erosion remain uncovered based on preservation and restoration point of view. Therefore, technological survey of such stone necessitates reducing demolition process by using conservational policies. According to petrography methods, structural analysis, XRD analysis and mechanical force testing according to International Society for Rock Mechanics standards based on ISRM (porosity, absorbing water, pressure resistance…) some samples have been experimented. As a consequence, illustrations show the mentioned type of stone is sedimentary type (Shale group) with weak superficial structure operates fragile under attack of aerobic parameters, caused by high permeability. Such mentioned stone, qualifies for craving but not suitable under aerobics. Under such circumstances, nothing found around Pasargadae site nor in any stone minds. So, it is said that these samples carried from other parts to the site of which the main source is still unknown.

Keywords: Pasargadae, Petrography, XRD analysis, ISRM standard, Achaemenid stone

1. Introduction

Pasargadae is an elevated plain located in the northwest of Fars province in hillsides branched out from Zagros Mountain. It is almost rectangular in shape with a sharp head which leads to a gorge that is called Balaghi Gorge. It is always fertile due to existence of Pasargadae gorge and it is residence of various ethnic groups (Shapoor Shahbazi, 1999: 9). Period of the rule of Great Cyrus was the peak of construction, civil developments and prosperous in the city of Pasargadae. According to Sami, after his death in 530 BC, Pasargadae was not center of attention anymore. So after the government of Darius I and construction of Persepolis in 518 BC the Pasargadae lost its importance totally in terms of being capital and changed in to a ritualistic city (Sami, 1997: 48).

Historical area of Pasargadae contains various sections that have been widely spread in the area and this kind of distribution in a wide area causes creation of the an illusion among the experts that the whole map shows scattered organization of tribal camps (Stronach, 1963: 69). These collected works in 2004 with No. 1106 have been registered in the UNESCO Heritage List.

In construction of tomb of Cyrus, Tomb of Cambyses, Throne of Solomon and the Holy Land only the white stone lime is used (Saeedi, 2005). In the construction of canals of Chahar-bagh, sandy limestone is used while in the construction of three palaces two sets of black and white stones are used. White stone are used in construction of floor, walls and cutting of columns, black stones are used in the head and base of columns and doorways. Unfortunately, the head of columns are completely destroyed and no trace of it is left (Figure 2), but the basic columns and doorways are still remained and their destruction trend continues (Figure 1).
According to studies conducted at Pasargadae complex, considerable research has been performed on samples of white stone in this collection. Perhaps this is because most part of the collection is made using these stones. In this regard, we can refer to studies conducted in this area in various user fields and recognition of white by the researchers: Pasargadae study (one report of excavations conducted by the Iran Institute of Studies-Britain, from 1961 to 1963) by David Stronach in which conducted studies are reviewed. Study of protection and restoration of Persepolis and other Fars archaeological sites in 1972 by Giuseppe Tillia. In which a brief research has been conducted on Pasargadae, Pasargadae and the tomb of Achaemenid Cyrus, review of Gholam Reza Vatandoost, Fars Geology Foundation, 1997, by Ali Sami, removing of lichens, MA. Thesis, Isfahan University of the Arts, 2003, by Amir Reza Poormoghadam, introduction and evaluation of the construction process of Pasargadae historical complex, Fall of 2004, by Maryam Rakhshani and Babak Kial, Investigation of the structure of white stones, 2005 by Zahra Saeedi, etc. These works investigate how Pasargadae is constructed and its excavations and also technology of white stone are examined. According to conducted studies, white stones are the main materials used in different parts of the Pasargadae. The stone has a marble and dense texture with a fairly good hardness which has been remained over several years. In this stone type, various destructive factors show less effect so that these stones are almost durable.

Now the question is that why black stone compared with white stone have been more demolished and what is their combination. What are related factors of this degradation? Are destructions related to stone structure or not. Another question is that why the carvings and embossed works in the palace has been worked on the black stones. Is his issue is related to the stone structure or not.

The main topic of this project will be technology of black stones that will be investigated based on different methods of petrographic, XRD analysis and tests of mechanical strength of stone based on ISRM standard. In studies and researches conducted on the field of technology and analysis of black stones, no sample of operations of black stones was observed. For this reason, all studies in the project have been started from the very basis.

2. Methodology and performed techniques

The first part of the black stones technology is sampling. Therefore, the typical black rocks on doorways and pillars mechanical sampling method was used. Required samples selected from three separate parts of doorways and pedestal. Sample A selected from columns pedestal in the porch of a special palace, sample B selected from the pedestals of the Baaram palace and sample C selected from doorway of the Baaram palace. Approximate size of samples was a 5 x 2 x 2 cm. Sample A had almost too much damage and samples B and C were in better condition (Table 1).

Stone diagnostic tests have two important characteristics: 1) in place 2) laboratory analysis. The first test focuses on detecting the location of the stone and tests will be conducted on natural stones that are not destroyed or are little damaged. Laboratory analyses in addition to other test methods in many cases are associated with
degradation. Petrography, Mineralogy or chemical composition test of stone samples and physical tests are common. Important goal in all of these analyzes is to identify the species of stone, knowing the current condition and providing data to deal with stones for a long time. On the other hand, stone recognition tests help us to find alternative stones with the same composition features contributed to the historic monuments (Prikrul, 2006).

Study of the structure of stones by X-ray diffraction (XRD) and electrophotometric microscopy is the best method (Domingoa et al., 2008). When replacement of similar stones is required, structural combinations and petrographic characteristics of main stones are very important (Hyslop, 2006).

In the first part of the direction identification and evaluation of stone type, the petrographic method was used. In this method, microscopic sections of stone samples are prepared and they are photographed by electron microscopy (polarizing). Petrographic analysis is an accurate method in the analysis of stones and its value is not only in the diagnosis of the stone aesthetic but also is in detection of hidden geotechnical incompatibility which leads to rapid destruction (Hyslop, 2004). Using this technique helps to select the one stone for next restoration in a long time (eg Warnes, 1926; Ashurts and Kelly, 1980). Then according to the received images and structural studies of the internal structure of the stone, the typology of stone will be identified (Figure 3).

In the next section, the sample was analyzed by XRD analysis. Both methods of XRD (X-ray diffraction) and XRF (X-ray fluorescence) selected to identify the mineralogical and chemical composition (Park, 2009). XRD method used for qualitative identification of various minerals and materials in the Mineralogical phases (Nicol, 1975). For the testing of samples, stones were powdered and analyzed by X-ray. In this method, composition of the stone components and its percentage is determined that will help to identify the type of material. In stone identification, this method is very useful for identification of stones type based on obtained composition.

X-ray enters and moves into the core of the stone material in a fluid form. In recent years, this approach has significantly improved (Geraud et al. 2003).

In the next section, mechanical strength tests on stone based on ISRM standard (ISRM, 1985) was performed. According to this method, the sample loss rate, porosity, water absorption, permeability and compressive strength is measured. According to the study by resosky and Novick, two geologists in 1971, hardness of various types of stones were identified. According to these calculations and type of identified stones, amount of hardness can be calculated.

Porosity of the stones varies from 10 to 90%. High porosity of the stone is among features that causes severe weathering (Benevento et al., 2001). It should be mentioned that the carbonate sediments may contain high porosity after sedimentation, but the porosity greatly reducing reduces or removes after sedimentation processes, and ultimately, limestone porosity decreases during time after its completion (Hearatian Ardestani, 2006: 14).

The amount of stone moisture in saturated state has a direct relationship with stone type and texture in addition to be considered as an indicator of stone strength. Absorption of water is calculated by immersing the samples in water for 48 hours at 25 °C. This value is calculated from real samples of water absorption and a method that has been proposed by ICCROM (Falcone, 2003). In general, stones with crystalline texture and large hardening index have a loss feature lower than 2%. Dense and cemented stone have a loss feature between 2 to 15% while weak stones and hard soils have loss index and seismic waves speed higher than 15% (Fahimifar, 2002: 93). Accordingly, based on experiments, the amount of loss can be considered as a major factor in the destruction of stones.

Uniaxial compressive strength also indicates the compressive strength of the stones that is the maximum tension that stone can resist. If the tension exceeds the rock falls apart and the maximum tension tolerance of stones after which the stone breaks is called stone strength. It can be calculated by P: F / A equation. A is the surface on which tension is imposed and F is the force on the surface calculated as kilograms per cubic centimeter (Saedi, 2005: 26).

<table>
<thead>
<tr>
<th>Table 1. Sampling.</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>Sample Specification</td>
<td>Location of Sampling</td>
<td>Sample</td>
</tr>
<tr>
<td>2x2x5cm</td>
<td>Low resistance under slicing</td>
<td>A plinth of private hall in northern part</td>
<td>A</td>
</tr>
<tr>
<td>2x2x5cm</td>
<td>Low destruction</td>
<td>A plinth in Audience hall</td>
<td>B</td>
</tr>
<tr>
<td>2x2x5cm</td>
<td>Low destruction</td>
<td>Audience hall doorway</td>
<td>C</td>
</tr>
</tbody>
</table>
3. Results

According to petrographic experiments carried out on the samples and its composition, the identified black stone is of limestone type. Black stone sample in Pasargadae palace was Foraminifer of Pelagic type in the micritic field (fine CaCO$_3$ Crystals) in which some parts were in the form of tiny micrite crystals due to recrystallization grownup to sparite. Type of black stone used in the building was identified as limestone of shale type.

According to the theory of John Pettit John, limestones are composed of various coarse-grains or Allochems, micrite (very fine-grained carbonate as a matrix for elements which usually are larger) and sparite (coarse crystalline CaCO$_3$ in many limestones in the form of cement as the binding agent of Allochems) either deposited by waves or currents or formed in place. According to the analysis conducted on the samples and based on petrographic observations, micrite can be observed as black color carbon in textures and as sparite in the form of crystallized CaCO$_3$ veins.

Black stones in the Pasargadae area are of shale type limestone that its main ingredients of cement are clay minerals spread throughout the area and are destructed and lost over time. This caused the stones lose their strength and become flaky (Figure 3).

According to petrographic and microscopic experiments, black stones of this area have a spherical and elliptical structure and cement materials are placed in between the spaces. Animal fossils are found in stone formations which causes severe clastic structure of such stones. Shale is a tiny grain of detrital type that easily becomes laminated or broken along certain levels. These stones are among the most abundant sedimentary stones. Weathered shales make them more laminated. This is because of removing a portion of the cement from stone along lamination and expansion due to penetration of water in clay particles. Shales change in to a soft soil like clay due to severe weathering (Memarian, 1996: 195).

According to macroscopic and field studies of the sample stone, the black carbonaceous stone is black in color that is likely due to conditions of sedimentation environment and the presence of organic matter in the structure. Among typical features of this stone is some filled veins and crystalline white CaCO$_3$, which sometimes consist of coarse grain crystalline. Black or gray colors indicate the presence of more than one percentage of organic materials in the stone composition which shows their sedimentary in oxygen-deficient or low-oxygen environments. This indicates the sediments should be deposited in a quiet environment without enough oxygen current which depends on the depth of the sea (Sohrabi, 1996: 85). The mentioned features are consistent with the results of microscopic characteristics of black rock and black stone which in turn confirm the characteristics of the pelagic environment.

Based on conducted XRD test, the stone sample was made of CaCO$_3$ and SiO$_2$ compositions. The amount of CaCO$_3$ in the sample was 97% and the amount of quartz in the sample was 3%. This composition indicates the stone calcareous structure and based on the obtained results it has a weak structure (Figure 4).

![Figure 3. Crusted structure of black stone in plinths and corrosion in layers, By Authors.](image)

![Figure 4. A microscopic black stone in 20x zoom, Crystallized Caco3 in addition to fossils appeared like black dots, By Authors.](image)
Carbonate stones are considered as chemical and biochemical components which form the most important group of non-detrifal stones. Stones which have usually more than 50% carbonate minerals in CaCO$_3$ or aragonite form are called limestone. Both CaCO$_3$ and aragonite have the same chemical formula CaCO$_3$ with the exception that CaCO$_3$ crystallization is in rhombohedral system (trigonal) and aragonite crystallization is in the rhombic system. Since the high-magnesium CaCO$_3$ and aragonite are both unstable, all calcareous sediments gradually become low-magnesium CaCO$_3$. Carbonate stones are mainly of organic origin (John Pettit, 1990).

Some tests are conducted to determine the mechanical strength of stone based on ISRM standard that can be considered in the table (Table 2 and 3). According to the results of resistance, it was observed that sample stones have very little resistance and are easily crushed. The compressive strength was low with high porosity that indicates the loss of cementations materials in the structure of the stone. Hardness of tested stones based their internal structure and the condition was between 3 and 4. Accordingly, the amount of porosity in the sample A was much larger than samples B and C. This shows the continuing rapid degradation in the sample A. However, according to the selection of samples from different parts, different degradation process was reported that indicated growth and distribution of destruction in all samples.

Table 2. Resistance of Stone Samples.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Sample Specification</th>
<th>Location of Sampling</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2x5cm</td>
<td>Low resistance under slicing</td>
<td>A plinth of private hall in northern part</td>
<td>A</td>
</tr>
<tr>
<td>2x2x5cm</td>
<td>Low destruction</td>
<td>A plinth in Audience hall</td>
<td>B</td>
</tr>
<tr>
<td>2x2x5cm</td>
<td>Low destruction</td>
<td>Audience hall doorway</td>
<td>C</td>
</tr>
</tbody>
</table>

Table 3. Stress Resistance of Black & White stone.

<table>
<thead>
<tr>
<th>Resistance stress Kg.cm$^2$</th>
<th>Real load at the time of breakage D.H</th>
<th>Diameter Weight (gr.cm$^3$)</th>
<th>Volume (gr)</th>
<th>Cross section Diameter (cm)</th>
<th>Height or thickness (cm)</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>197</td>
<td>41540</td>
<td>2/664</td>
<td>913</td>
<td>342/73</td>
<td>36/85</td>
<td>Black stone</td>
</tr>
<tr>
<td>516</td>
<td>18910</td>
<td>2/467</td>
<td>701</td>
<td>284/19</td>
<td>37/39</td>
<td>White limestone</td>
</tr>
</tbody>
</table>

Stones usually are specifically layered and if these stones go out of their original environment and placed in an environment with new features under pressures in the opposite direction of the their structural pressures, then destructive factors will damage them in a shorter time and they will be damaged (Madani, 2002: 53). This is true for the studies sample black stone, and their application in the opposite direction of their layers can be considered as a reason for their destruction. Because the direction of layers and sedimentation of used shale stones is horizontal but this issue is not considered in the application of the stones, so pressure of other stones over long time causes cracks and separating black stones from their layers.

4. Conclusions

In this study, stone type, its structural composition, and strength were determined using petrographic methods, XRD analysis and ISRM. These samples were among very weak sedimentary stones, which their internal structure damaged over time and their cement material and adhesive materials separated. Accordingly, its resistance decreased and the changed in to a flake-shaped stone being separated from the main surface. One of the features of shale stones is their flexibility and their sedimentary feature and layered surface structure makes them suitable for engraving and carving.

According to collected data from black stones of Pasargadae, the sample sedimentary stones were calcareous that are among the shale stones. Physical properties of shale stone was one of the major causes of destructions on the stones. Features of this stone were also considered as a factor to be used for carvings and embossed works in the past because their structure was more flexible than the other lime stones and allowed for easier cuttings by stonemcut.
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Degradation of Engraved Stone and Renders from Qasr Qarun Temple in Fayoum Oasis, Egypt

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Abstract

Qasr Qarun temple is located in the western edge of Qarun Lake in El Fayoum Governorate. It is about 40 km from the capital El Fayoum and 120 km South east of Cairo, Egypt. It is dedicated to god Sobek and it was erected during the Ptolemaic Period (304–30 BCE). The palace is surrounded by some remains that are a Roman bath, two temples, several fresco-decorated houses and a fortress. Qasr Qarun temple was built from early Eocene limestone which is coming from Qarun Quarry. Joint mortars strengthen the masonry and renders cover also the inner face of the walls that can be engraved. These renders and mortars were made of lime and contain also gypsum and quartz. Both the stones and renders suffer a lot of degradation patterns (scaling, powdering etc.). Hygroscopic salts and swelling clay minerals are responsible for these degradations that induce to a weakening of the strength resistance of the materials. The present work aims to evaluate the respective contributions of these factors in the degradation process by the way of microscopic observations in order to characterize the degradation patterns and to determine the causes of the main degradation, A mineralogical characterization of samples has been performed according to the powder method using X-Ray diffractometer (XRD) and specific treatments dedicated to the characterization of their clayish content. Last, the paper proposes a new conservation approach taking into account the causes of the implemented degradation processes.

Keywords: Engraved limestone, Mortars, Hygroscopic salts, Swelling clay minerals, Degradation

1. Introduction

Because of degradations affecting the building materials, a conservation study of the engraved stone and renders from Qasr Qarun Temple in Fayoum Oasis, Egypt has been started up (Figures 1 and 2). Qasr Qarun temple is located in the western extremity of Qarun Lake in El Fayoum Governorate. It is about 40 km from the capital El Fayoum (Bunson, 2002). The site had enjoyed great importance during the Greco-Roman Period as here was the beginning of the caravan route to Baharia Oasis in the Libyan Desert (Christina, 2012). This temple is also called Dionysius Qasr Qarun and was a staging area for caravans to Baharia Oasis in the Libyan Desert. It is dedicated to the god Sobek, from the Ptolemaic Period (304–30 BCE), and dominates beside the region (Aldred, 1980). The palace is surrounded by some remains of a Roman bath, two temples, a number of fresco-decorated houses, and a fortress (Hewinson, 2008).

The temple appears simple and roughly square from outside. The temple is a place of a lot of corridors, chambers, tunnels, and spiral staircases that all end on the roof (Figure 3). Oracular secret niches are part of the design. There was once a roof chapel on the structures as well. This temple is one of the very few ones in Egypt which have accessible roofs (Margaret, 2002; Paul & Ian, 2000).

Qasr Qarun temple was built from early Eocene limestone which is mainly coming from Qarun Quarry (Christina, 2012). Joint mortars strengthen the masonry. A render covers also the inner face of the walls that can be engraved (Figures 1 and 3). Both the stone and renders surfaces suffer a lot of degradation patterns (Figures 1, 2 and 4). The characterization of materials in historical artifacts is a key issue for a good conservation diagnosis.
Torraca, 1982). Abd El Haddy (1990) and Kostler (1993) explain indeed that it is more particularly indispensable to characterize the chemical and mineralogical constituents of valuable and scarce objects in order to conserve and restore better. More, it should be ideally performed using non-destructive approaches (Hélène, 2006; Bushell, 1970; Harper, 1988).

These additional analytical data inform also on the methodology of their application or on ancient technologies used for their preparation. These data are especially useful to art historians, archaeologists and conservators (Weber, 1977; Grag, 1998; Eric and Clifford, 2010).

2. Methods

A sampling campaign has had to be implemented in order to characterize the degradation patterns and to determine the causes of the main degradation. Polarized light microscopy (PLM) was carried out on the samples by Olympus SZ-40 stereomicroscope and Nikon E600 microscope.

Figure 1. Qaser Qarun temple: the main door (East façade; a) and the plans for the east and west façades (b) that are both 18.8 m (authors measures). Please note the high of the rising damps that affects the 5 first meters of the North façade. Ancient (using the same limestone as implemented during its erection) and recent restorations (stones blocks having a whitish color) also are visible.

Figure 2. Qaser Qarun temple: the North (a) and the South (b) sides of the temples that are both 28.6 m length (authors measures). Please note that the important high of the rising damps that roughly corresponds to the black coloration line on the photos. Please note that this black coloration is more visible on the North side than the South side; we can then suppose that microorganisms could be responsible of it. The part where both render and joining mortars are degraded only affects the half East part of the façades up to almost 2.5 m.
The mineralogical characterization of samples was performed according to the powder method using a 0-20 Bruker D8-Focus X-Ray diffractometer (XRD) equipped with a Cobalt tube as the X-ray source ($\lambda_{CoK\alpha} = 1.7902$ Å) at 35 KV and 40 mA. The angle step was 0.02°2$\theta$ and the time by angle step was 24.5 sec/step.

Specific treatments of the clayish content have been then performed according to the classical protocols of samples preparation (Moore & Reynolds, 1989): decarbonation of the samples, particle size separation using Stocke’s law in order to conserve only the $< 4\mu$m fraction, oriented preparation on a glass plate that was analyzed first when it was dried. An ethylene glycol treatment has been applied after and last the preparations have been heated (500°C).

3. Materials and sampling

10 samples of limestone have been collected from the temple walls in order to find out their mineralogical content and to determine the nature of the difference among the different kinds of stones. Different places of the temple have been sampled at various distances from the floor and from the different chambers of the temple. 6 samples of renders have been collected. 7 samples of salts were collected as efflorescences or subeflorescences. They all have been observed and analyzed. 4 samples of stones and 4 of render and joint mortar have been treated in order to study the clayish content. All the samples are briefly presented in Tables 1 and 2.

4. Results

In situ observations show that the structures of the Qasr Qarun Temple and its building techniques depend on several kinds of limestone that differ from color, rigidity and strength. The limestone blocks which were used in the construction of the temple are different from those that were used to build the Funerary chamber in the end, the three doors in the temple and the thresholds and loading areas. These last were made in the strongest and hardest limestone that is present on the site. In this case, the analyses showed that it is only made of calcite (ex. FS8 in Table 1). In the samples coming from Funerary chamber veins of quartz ($SiO_2$) are present.

Figure 3. Qasr Qarun Temple: general view from the three main halls (a) and the funerary chamber (b).
Others samples from different places of the temple such as the normal walls of the temple contain also traces of hygroscopic salts that are gypsum (CaSO₄·2H₂O), bassanite (CaSO₄·0.5H₂O) and halite (NaCl). Clay minerals are detected on the XR diffractograms because of the presence of a small line in the 10°-20°CoKα region, a line in the 11.5-12.5°20CoKα region and a bulge in the 5-7°20CoKα region.

These salts are visible on the surface as efflorescences or sub-efflorescences under detached parts of the stone surface. Otherwise, the microscopic observations show that different crystallized forms of salts are present inside the limestone structures such as lenticular, drapery, needle, powder and micro granular forms (Hélène, 2006; Bushell, 1970; Figure 5).

The clay minerals content has been determined in several samples of both limestones (Figures 6 and 7). Figure 6 shows that swelling clays (montmorillonite) are present in the limestone because of the swelling under ethylene glycol treatment that lead to the displacement of the 001 diffraction line from 1.479 to 1.721 nm. The comparison of the different samples shows (Figure 7) that they all have the same clay mineral families.

Mortars are assumed to have been locally applied on the limestone surfaces in order to help the funerary engraving. They contain calcite and quartz as the principal components (Table 1). Gypsum has been detected as well as other dehydrated forms (anhydrite (CaSO₄) and bassanite). Other salts are present such as trona as traces and halite. Observations under the microscope and analyses allow showing the presence of salts on the outer surface and also within the internal structure of the render.

**Figure 4.** Degradation patterns affecting Qaser Qarun Temple’s walls surfaces including: desquamations, bleaching that can be induced by the presence of hygroscopic salts and biological colonization as a honeycomb that 10 cm length (detail of the upper part of the funerary chamber; a), blistering and scaling at the low part of the picture and at the upper part, blackening because of possible soil deposit or microorganisms colonization (blistering is around 3 cm length; b) scaling and blistering that are linked to halite crystallization according XRD analyses (c).
XRD analyses on renders powders also show the presence of clay minerals (presence of a small line in the 10°2θCoKα region, a line in the 11.5-12.5°2θCoKα region and a bulge in the 5-7°2θCoKα region) in weak quantities. The clay mineral cortege is different in the limestone and is composed of chlorite and illite in very weak quantities (Figure 7).

The engraved stones and renders from Qasr Qarun Temple status in the Burial chamber are in bad conservation conditions (Figure 4). They show degradation patterns including missing part, powdering, desquamation, blistering and detachment, scaling and blackening according to Anson-Cartwright et al (2008).

Efflorescences and subefflorescences samples have been analyzed (Table 2): the present hygroscopic salts mainly are halite and compounds containing sulphates. More precisely, different hydrated forms of CaSO₄ and MgSO₄ and traces of thenardite (Na₂SO₄) are present. The presence of these hydrated forms can be explained because of a partially dehydration of the samples at the time of the analyses. Traces of oxalates (weddellite, CaC₂O₄·2H₂O) and niter (KNO₃) are also present. These last salts come from a biological activity.

Figure 5. Example of different forms of salts crystallizations that are present in the limestone (optical microscopy investigation; scale: the width of each pictures is about 3cm length): lenticular (a), drapery (b) and microgranular (c) forms.

Figure 6. XRD patterns of the clay minerals content of Fayoum Stone 10 showing the presence of montmorillonite, illite, kaolinite and traces of chlorite.
Table 1. Presentation of the limestone and renders samples and their mineralogical content as determined using XR Diffraction (powder method). Their relative presence is estimated taking into account the measured intensities of the main diffraction peaks.

<table>
<thead>
<tr>
<th>Sample reference</th>
<th>Location</th>
<th>Clay minerals</th>
<th>Quartz</th>
<th>Calcite</th>
<th>Trona</th>
<th>Whewellite</th>
<th>Halite</th>
<th>Gypsum</th>
<th>Bassanite</th>
<th>Anhydrite</th>
<th>Niter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fayoum stone 4</td>
<td>Limestone main Halle</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
<td>tr</td>
<td>+</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Fayoum stone 6</td>
<td>Limestone from wall of the temple</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
<td>tr</td>
<td>+++</td>
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<td>tr</td>
</tr>
<tr>
<td>Fayoum stone 8</td>
<td>Limestone Funerary chamber</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
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<td>+++</td>
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<tr>
<td>Fayoum stone 10</td>
<td>Limestone form wall of the temple</td>
<td>tr</td>
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<td>tr</td>
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<tr>
<td>Fayoum stone 13</td>
<td>Limestone from door</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
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<td>+++</td>
<td>tr</td>
<td>tr</td>
<td>+</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Fayoum mortar 1</td>
<td>First door</td>
<td>tr</td>
<td>+++</td>
<td>+</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
<td>tr</td>
<td>+</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Fayoum mortar 2</td>
<td>Funerary chamber</td>
<td>tr</td>
<td>+++</td>
<td>+</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
<td>tr</td>
<td>+</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Fayoum mortar 3</td>
<td>Second door</td>
<td>tr</td>
<td>+++</td>
<td>+</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
<td>tr</td>
<td>+</td>
<td>tr</td>
<td>tr</td>
</tr>
<tr>
<td>Fayoum mortar 4</td>
<td>Fayoum mortar 4 main hall</td>
<td>tr</td>
<td>+++</td>
<td>+</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
<td>tr</td>
<td>+</td>
<td>tr</td>
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<tr>
<td>Fayoum mortar 5</td>
<td>Main gate of the temple</td>
<td>tr</td>
<td>+</td>
<td>+</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
<td>tr</td>
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<tr>
<td>Fayoum mortar 6</td>
<td>Wall of the temple</td>
<td>tr</td>
<td>+++</td>
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<td>+++</td>
<td>tr</td>
<td>tr</td>
<td>+</td>
<td>tr</td>
<td>tr</td>
</tr>
</tbody>
</table>

Legend: ++++; large majority constituent, ++; secondary constituent, +++; main constituent, +; present, tr; present in few quantities

Table 2. Presentation of the salts samples and their mineralogical content as determined using XR Diffraction (powder method). Their relative presence is estimated taking into account the measured intensities of the main diffraction peaks.

<table>
<thead>
<tr>
<th>Sample reference</th>
<th>Location</th>
<th>Quartz</th>
<th>Calcite</th>
<th>Weddellite</th>
<th>Halite</th>
<th>Gypsum</th>
<th>Bassanite</th>
<th>Hexahydrite</th>
<th>Pentahydrite</th>
<th>Starkyte</th>
<th>Thenardite</th>
<th>Niter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt 1</td>
<td>First door (First hall)</td>
<td>+</td>
<td>+++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Salt 2</td>
<td>Second door (Second hall)</td>
<td>++</td>
<td>+++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Salt 3</td>
<td>Main gate outside</td>
<td>tr</td>
<td>+++</td>
<td>+</td>
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<td>+</td>
<td>+</td>
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<td></td>
</tr>
<tr>
<td>Salt 4</td>
<td>Funerary chamber</td>
<td>+</td>
<td>tr</td>
<td>+++</td>
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<td>+</td>
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<tr>
<td>Salt 5</td>
<td>Main gate outside</td>
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<tr>
<td>Salt 6</td>
<td>Funerary chamber</td>
<td>tr</td>
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<td>+++</td>
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<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Salt 7</td>
<td>Main hall first one</td>
<td>+</td>
<td>tr</td>
<td>+++</td>
<td>tr</td>
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<td>+</td>
<td>+</td>
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</tr>
</tbody>
</table>

Legend: ++++; large majority constituent, ++; secondary constituent, +++; main constituent, +; present, tr; present in few quantities
5. Discussion

The renders are made of carbonated lime with quartz as the sand. They contain clay minerals and traces of gypsum. Lime-base mortars were commonly made during the Greco-Roman period in Egypt and conversely to the previous Egyptian historical periods where gypsum only was used. The first renders were made from mud or clay. These materials were used because of availability and low cost. Egyptians utilized gypsum mortars for lubricating the beds of large stones in order to move them into their appropriated position (Vitruvius, 1931). However, these materials were not efficient in the presence of high levels of humidity and water. Builders of Roman Empire used lime based mortars extensively. Vitruvius, a Roman architect, provided basic guidelines for lime mortar mixes (Vitruvius, 1931). However the earliest documented use of lime as a construction material was approximately 4000 B.C. according to Boynton (1980) when it was used in Egypt for plastering the pyramids (McKee, 1980). This is challenged by Lucas & Harris (1962) and Ghorab et al. (1986) who indicate that the Egyptians did not use lime in construction but only gypsum until Roman times (Lucas & Harris, 1989). The presence of clay minerals is not well understood here but one can suppose that these minerals were present in the sand. Last, gypsum only seems to be present here because of the migration of hygroscopic salts in the masonry.

The degradation patterns of the engraved stones and renders from Qasr Qarun Temple can be attributed to intrinsic factors such as the presence of hygroscopic salts and the presence of swelling clays in the limestone. Hygroscopic salts are considered as one of the most deteriorating factors affecting all components of archaeological buildings. The salts are responsible of lot of the observed degradation patterns such as loss of materials, blistering, powdering and chromatic changes as described also in literature (e.g. Grossi, 1997, B. Smith, 2008 and Rodriguez-Navarro, 1997). The intensity and velocity of the degradation depend mainly on the type of salt. The most deteriorating agents are the sulphate- base ones that are present in important quantities. The deterioration of the building blocks is also visible on the recent ones that come from recent restorations.

![Figure 7](image.png)

**Figure 7.** Comparison of the XRD patterns of the clay minerals content of the limestone samples. These samples have the same clay minerals content as presented in figure 6 (Example of Fayoum Stone 10’s sample). FS15 content is very low.
Their origin seems to be twofold. The observations as shown on figures 1 and 2 suggest that they mainly come from a close aquifer. They probably are transported in large part masonry by the way of rising damps that reach an important height. In another hand, the limestone seems to contain naturally hygroscopic salts as the observed crystallized forms in the stone suggest it.

The degradation mechanisms involving the soluble salts is not still well understood. However, the variation of moisture in the masonry is sufficient to allow their migration to the surface where they induce a differential behavior of the materials and a quick and strong degradation of the surface. Last, their important quantity in the both renders and limestones, their migration according to rising damps and variations of environmental conditions lead to a huge process of fragmentation of stones and renders and raise fears of a large deterioration of the temple.

Clay minerals are natural components of stones and are generally present as minor component in some ornamental and building limestone. They also are generally considered as harmful constituent of buildings stones and have been recognized to be a major problem in the conservation of cultural heritage (Rodriguez-Navarro, 1997). More precisely, the swelling clay minerals from the smectites group (montmorillonite) as detected in the limestone can lead to the deterioration of the stone surface as scaling and loss of material according to Berthonneau (2013) even they are present in weak quantities. They are very sensitive to the presence of water as a liquid or a gas and they develop strong internal pressures during the swelling process (Berthonneau, 2013; Moore & Reynolds, 1989). Because of important variations of humidity and temperature, these clay minerals seem to play a serious role in the damage of the building stones of the temple.

Figure 8. Comparison of the XRD patterns from limestone and mortar. The clay minerals content is different as mortar sample only shows the presence of chlorite and illite.

6. Conclusions and perspectives

The building stones of Qasr Qarun Temple are made of limestones that contain a very little detrital fraction (quartz, illite, montmorillonite). They are covered by mortars that were made of lime and sand. This last one seems to contain few impurities (chlorite, illite).

Stones from the structure, engraved stone and renders from status in are in bad conservation condition. They show lot of degradation patterns including desquamation, detachments, scaling and missing parts. Hygroscopic salts are the causes of the observed degradations that affect them. The presence of salts is one of the main causes of deterioration of porous art objects such as stone statues. Crystallizing salts may be locally concentrated as
efflorescences on the artwork surface or as less apparent sub-efflorescences in the subsurface of the porous materials that cause mechanical damages of artworks. Salts are hence considered as one of the most dangerous degradation agents affecting cultural heritage and their removal using appropriate cleaning procedures is one of the principal goals of the restoration of cultural heritage. This deterioration is especially serious on porous systems such as engraved stones. Salt removal by appropriate cleaning procedures should be one of the restoration principles to implement. It needs previously to stop the salts inputs are stopped. It is also a huge work because of the whole thickness of the stones that contain them.

In another way, the presence of swelling clays (smectites) in the limestone is also an important conservation issue. They help the weakness of the internal structure of the building and engraved stones. Thus a treatment to block the swelling process could be theoretically forecast on desalinated engraved stones in order to stop the deterioration of the surface of the engraved stones.

Last, the conservation and the restoration according traditional methods of conservation and treatments that are currently implemented should be readapted in the highlights of this work. The regular use of lime and sand with gypsum for losing mortar and the reuse of the losing parts of stone block as rebuilding materials should be prohibited. In another hand, the use of gypsum and lime as mortar materials between blocks should be replaced with materials containing no hygroscopic salts nor swelling clay minerals.

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Study on the Consolidation Mechanism of the Weathered Stone with Clay Minerals

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Abstract

In order to investigate the consolidating mechanism of the weathered stone monuments containing clay minerals, the consolidating effects were studied by applying 9 types of the ethylsilicates consolidants onto the weathered stone containing clay minerals. XRD and SEM were used to find the influence of the clay minerals. The XRD results showed that the lattice spaces of the clay minerals was changed by infiltrating the consolidants. Through the investigation of the reaction mechanism between the stone samples containing clay minerals(smectites) and the consolidants, both the expansion and the shrinkage of the lattice space were found. On the contrary, in case the swelling inhibitors were applied to the stone samples containing the clay minerals, the changes of the lattice space were reduced.

Keywords: Consolidation, Mechanism, Stone, Weathering, Clay minerals

1. Introduction

The weathered stone cultural assets which are in particular exposed to outdoor contain clay minerals with swelling property irrespective of the stone types. It has been thought that the clay minerals are causing the internal stresses among mineral particles of stone structure (Oort, 2003).

In this study, the consolidating mechanism and consolidating effects of the consolidating agents (consolidants) were investigated, which have been used to the weathered stone monuments on the conservation field. In order to investigate the consolidating mechanism of the weathered stone monuments containing clay minerals, the consolidating effects were studied by applying 9 types of the ethylsilicates consolidants to both the tuff and the shale containing clay minerals.

2. Experimental procedures

For experiments 9 types of consolidants were employed (Table 1). The consolidated minerals were characterized by a x-ray diffraction (XRD, Philips, PW 3710, Holland), and scanning electron microscopy (SEM, Hitachi 2300, Japan).

3. Results

Because the gelation rates and the contents of the silica for each consolidants were different respectively, the properties of gelation forming silica gel and the infiltrating efficiency of the consolidants were slightly different. The physical properties such as a bulk density, a porosity, a total water absorption rate, and a capillary water absorption rate were changed in all stone samples after consolidating experiments. The values of bulk density were increased, and the values of the porosity, the total water absorption rate, and the capillary water absorption rate were reduced. This is because the stone particles were effectively coated with silica gel on the surface and the inside of the stone samples forming the three-dimensional net structures from the ethylsilicate consolidants after infiltration into the stone samples.
Table 1. Properties of the Consolidants.

<table>
<thead>
<tr>
<th>Consolidants</th>
<th>Contents of silicate (%)</th>
<th>Gelation rates (%)</th>
<th>Density (g/cm³)</th>
<th>Viscosity (mPas)</th>
<th>Colors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unil Sandsteinfestiger H</td>
<td>75</td>
<td>30-34</td>
<td>0.88</td>
<td>1.6</td>
<td>none</td>
</tr>
<tr>
<td>Funcosil Steinfestiger 300</td>
<td>99</td>
<td>30</td>
<td>1.0</td>
<td>1.2</td>
<td>none</td>
</tr>
<tr>
<td>Unil Sandsteinfestiger OH 100</td>
<td>100</td>
<td>40-46</td>
<td>0.99</td>
<td>1.6</td>
<td>none</td>
</tr>
<tr>
<td>Unil Sandsteinfestiger OH</td>
<td>75</td>
<td>-</td>
<td>0.95</td>
<td>1.6</td>
<td>none</td>
</tr>
<tr>
<td>Funcosil Steinfestiger 100</td>
<td>20</td>
<td>10</td>
<td>0.79</td>
<td>1.1</td>
<td>yellowish</td>
</tr>
<tr>
<td>Unil Sandsteinfestiger OH 1:1</td>
<td>37</td>
<td>15-17</td>
<td>0.87</td>
<td>1.6</td>
<td>none</td>
</tr>
<tr>
<td>Funcosil Stone Strengthener OH</td>
<td>75</td>
<td>30</td>
<td>0.94</td>
<td>1.2</td>
<td>yellowish</td>
</tr>
<tr>
<td>Funcosil KSE 300 E</td>
<td>40</td>
<td>30</td>
<td>0.9</td>
<td>1.1</td>
<td>yellowish</td>
</tr>
<tr>
<td>Silres BS OH 100</td>
<td>100</td>
<td>-</td>
<td>0.99</td>
<td>1.6</td>
<td>yellowish</td>
</tr>
</tbody>
</table>

For the consolidants with high contents of the silica among the 9 types of the consolidants, both the decreasing effect of the porosity and the restrain effect of water permeation were good. The results were considered that the gelation in pores of the stone samples was good as much as the contents of silica. Although all consolidants can form the silica gels and reveal the sufficient consolidating efficiency, the probability causing the secondary weathering such as slaking, swelling, and shrinking was found by SEM and XRD analyses about the swelling property of the clay minerals (Figures 1 and 2).

The XRD results showed that the lattice spaces of the clay minerals was changed by infiltrating the consolidants (Figure 3 and Table 2). In case the swelling inhibitor was employed to the stone samples containing clay minerals before consolidation, the changes of the lattice space were reduced (Figure 4).

Figure 1. Cracks of consolidants (Silres BS OH-100) inside shale. (a) X100, (b) X500, (c) X1,000, (d) X2,500.

Figure 2. Picture of mudstone surface after consolidation with Silres BS OH-100 (example).
Table 2. Variation rates of lattice parameters of shale after consolidation.

<table>
<thead>
<tr>
<th>Consolidants</th>
<th>(d_{001}(\text{Å}))</th>
<th>Change (Å)</th>
<th>Rates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone</td>
<td>14.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>15.55</td>
<td>0.68</td>
<td>4.57</td>
</tr>
<tr>
<td>Unil Sandsteinfestiger H</td>
<td>15.15</td>
<td>0.28</td>
<td>1.85</td>
</tr>
<tr>
<td>Funcosil Steinfestiger 300</td>
<td>14.52</td>
<td>-0.34</td>
<td>-2.30</td>
</tr>
<tr>
<td>Unil Sandsteinfestiger OH 100</td>
<td>15.23</td>
<td>0.36</td>
<td>2.41</td>
</tr>
<tr>
<td>Unil Sandsteinfestiger OH</td>
<td>14.20</td>
<td>-0.67</td>
<td>-4.50</td>
</tr>
<tr>
<td>Funcosil Steinfestiger 100</td>
<td>15.15</td>
<td>0.25</td>
<td>1.71</td>
</tr>
<tr>
<td>Funcosil Stone Strengthener OH 1:1</td>
<td>15.12</td>
<td>0.25</td>
<td>1.71</td>
</tr>
<tr>
<td>Funcosil KSE 300 E</td>
<td>17.05</td>
<td>2.18</td>
<td>14.66</td>
</tr>
</tbody>
</table>

Figure 3. XRD patterns of shale after consolidation.

Figure 4. Variations of lattice parameter of shale with di-aminobutane di-hydrochloride as a swelling inhibitor. (left: without inhibitor, right: with inhibitor).

Figure 5. Reaction of swelling inhibitor to clay minerals inside stone.
4. Conclusions

Through the investigation of the reaction mechanism between the stone samples containing clay minerals (smectites) and the consolidants, both the expansion and the shrinkage of the lattice space were found. Such the expansion and the shrinkage can cause the physical damage to the stone that can change the crystal structure of rock-forming minerals and cause the internal stresses between mineral particles. For instance, some cracks and exfoliations were caused on the stone surface after consolidating the stone sample consisted of diatomite.

On the contrary, in case the swelling inhibitor that can reduce both the expansion and the shrinkage were applied to the stone samples containing the clay minerals, the changes of the lattice space were reduced. The inhibiting mechanism of the swelling was considered that the internal stress was mitigated by modifying the surface properties and by affecting as a buffer layer after infiltrating both the swelling inhibitors and the consolidants on the surface of the mineral particles (Figure 5).

References

The Stone Gates of the Royal Palace in Patan (Nepal):
A Peculiar Cleaning Problem Solved by the Use of Laser

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Abstract
The paper reports on the conservation treatment of one of the stone gates of the Royal Palace in Patan (Nepal). The stone mineralogical and petrographic characteristics are described, along with the major forms of decay. Short historical information on the Palace is given as well. The most difficult part of the conservation treatment was the removal of a thick layer of bitumen, applied in the past, which disfigured the finely carved panels. After several unsatisfactory trials with organic solvents, the cleaning was accomplished by the use of an Nd YAG laser equipment by the Italian El.En Group Florence.

Keywords: Sandstone decay, Laser cleaning, Bitumen removal, Patan Royal Palace

1. Introduction

The project for the conservation of relevant parts of the Patan Royal Palace in Nepal, conducted by the University of Applied Arts Vienna - Institute of Conservation (under the direction of Prof. Gabriela Krist) and the Kathmandu Valley Preservation Trust (KVPT) is an important example of international cooperation. It is supported by Eurasia-Pacific Uninet (EPU), University of Applied Arts Vienna and Kathmandu Valley Preservation Trust (KVPT). Eurasia-Pacific Uninet is a network which aims at establishing contacts and scientific partnerships between Austrian Universities, Universities of Applied Sciences, other research institutions and member institutions in East Asia, Central Asia, South Asia and the Pacific Region (http://www.eurasiapacific.net/ access: 04/02/2013).

A team consisting of senior conservators and a group of undergraduates from the university were working together with architects and local craftsmen from KVPT. Their activity focused on the conservation of different parts of the Palace Complex. The conservation of one of the stone gates of the Royal Palace is one of the many activities performed during four summer campaigns dating from 2010 to 2013. The preliminary scientific investigations were carried out by the University of Applied Arts Vienna, Institute of Conservation Sciences. A petrographic characterization of the stone was done and the black, disfiguring organic coating was analyzed to be bitumen. Neither archival nor photographic documentation is available to comprehend when and why the bitumen was applied. After some cleaning attempts with solvents, preliminary tests with different laser equipment were performed, and were very encouraging. In the campaign of 2013 a modified laser Eos 1000 LQS (Long Q-Switch) by the Italian El.En. Group, Florence was transported to Patan and was successfully used for the cleaning of the stone carvings of one of the gates. The methodology adopted and the results achieved will be illustrated later in this report. The strong didactic component, the scientific support of the university and the good outcome of the cleaning conservation treatment, add value to this cooperative initiative for the preservation of a site included in the UNESCO World Heritage List.
2. The monument

The Patan Royal Palace was built in the 14th and extended in the following centuries. Unfortunately, in 1768, it was heavily damaged by the ruler Prithvi Narayan Shah. More recently, further damages were produced by a strong earthquake in 1934.

The Royal Palace takes the eastern side of the Durbar Square and the whole complex is a part of the UNESCO World Heritage Site. In 1979, the World Heritage Committee approved Nepal’s application to place seven sites in the Kathmandu Valley on the World Heritage List. The seven sites that have been chosen stand representative for the Cultural Heritage of Nepal, the architecture, art and religion. The Seven Monuments of the Kathmandu Valley are: The Durbar Squares of Kathmandu, Patan and Bhaktapur, the Buddhist Stupa of Swayambhunath and Boddanath, the Hindu temple complex of Changu Narayan and Pashupatinath (see the UNESCO, Master Plan for the Conservation of the Cultural Heritage in the Kathmandu Valley, Paris 1981, p. 9).

Along the side of the Palace facing the Durbar Square two monumental gates open at both sides of the Degutaleju Temple. The oldest known drawing of the gates dates from 1845 (Figure 1) and the oldest photographic documentation from 1863 (Figure 2) (KVPT, 2007). It was hypothesized that the gates resulted from a collage of indefinable pieces after the earthquakes, but the historic documentation (drawing and photo) proves that the gates were part of the complex at least since the 19th century.

An assumption of the history of origin of the gates is probably limited to the period of time from 1640 until 1734. Even if the oldest graphical documentation is from 1845, the date of erection in the period from the second half of the 18th and the first half of the 19th century can be excluded. Patan was not an independent kingdom during this time range. New building projects during a period with no political head in the city of Patan would have been irrelevant.

Unfortunately the gates look disturbed and were reassembled at least once after the devastating earthquakes from 1833 and 1934. Maybe this reassembling, resulting in a very inhomogeneous picture, is the reason for the “collage” hypothesis. The hypothesis says that the gates are a collage of stone blocks, which were found after the earthquakes and could not be placed back on their original position.

The main parts of the gates consist of fine carved stone blocks with motives of the so called Śakti cult. Both gate constructions are integrated in the brick masonry. The backsides of the gates are in direct contact with the brick wall. On some stone blocks red paint was found. It is assumed that this paint rests (drops) are results of the omnipresent worshipping rites and not rests of an original surface layer.

When the cooperative working campaigns between Nepal and Austria, started in the summer of 2010, the
gates were covered with a dark coating which was thought of as a result of earlier conservation works. The coating badly influenced the optical appearance and caused damages to the original stone surface. Therefore, the main interest was to remove the black coating (Figure 3 and 4).

3. The diagnostic study

3.1. The type of stone

Samples coming probably (according to the KVPT responsible officers) from the same quarry used for the carved reliefs were studied and compared with the single sample which could be taken from the original reliefs: polished thin sections were prepared and observed under a polarized light microscope (PLM) and a scanning electron microscope equipped with Energy Dispersive Spectroscope (SEM/EDS) for the mineralogical and petrographic characterization; on the quarry samples, water absorption by capillarity and drying rate were measured in order to understand the interaction of the stone material with water. The stone can be defined as a clastic sedimentary rock, namely fine grained quartz sandstone of yellowish color coming from clayey and iron-rich particles. The size of the phyllosilicates that are visible in the polarizing microscope is too big for clay but too small for detritic mica. They are likely to be sericite. Iron oxides and hydroxides together with fine clay compounds are found on the surface of the quartz and feldspar grains and form a kind of binder. An average total porosity in the range 32 – 23 Vol.% of the quarry stones was estimated. The porosity accessible to water, measured by full immersion at 24h, spans from 29 to 20 Vol%. The full drying following water saturation by immersion, measured in laboratory conditions (25 °C, 50 %RH) was achieved in about 31 hours, when constant weight was reached. From this result it seems that, despite of the relatively high clay content, no significant amounts of water are held back during drying. Altogether, the stone can be considered as highly absorptive material.
3.2. The forms of decay

The most important and evident form of decay can be described as “biological colonization” according to the ICOMOS-ISCS Illustrated glossary on stone deterioration patterns. Salt efflorescence is also present, even if in the monsoon period rather rare. However, flaking, scaling, and peeling, observed in some parts, can be correlated to the action of salts.

Considering the climate of the Kathmandu Valley it is not surprising that the biological growth is very intense and spread on all stone surfaces. The annual climatic cycle of Nepal is divided into three seasons: Winter is from October till February, the hot and dry season is from March till June and the monsoon season is from June till September. In the wet season 80 % of the total precipitation occurs. The temperatures in summer are between 24° and 30°C and during winter the average temperature is 10°C (minimum of -3°C). These conditions support the vegetative growth in the Kathmandu Valley during the whole year. Thick layers of lichens and moss influence the readability of the ornamental decoration which becomes invisible. Next to the aesthetical issue, the condition of the stone can be negatively affected. In connection with biological colonization water is kept even longer in the stone matrix, plants colonize places where water is accessible, extending roots into joints and fractures. As the roots grow, they can widen joints and cracks and cause stone breakages. They may also contribute to keep areas damp.

The salt deterioration of some parts of the gates is another problem. Natural biological deterioration process plays a major role as source of water soluble salts (human urine, animal droppings, etc.). It is also possible that the presence of the so called nitrification bacteria (found in the soil) is responsible for the nitrate concentration found in the stones (Leiner, S., 2009, p. 76). The salt dissolution/crystallization cycles lead to the formation of efflorescence and sub-efflorescence and to the disaggregation of the stone structure resulting in the loss of important carved stone surface (Charola A.E., 2000).

Another source of salts is Portland cement which was used for the reassembling and the pointing of joints during the reconstruction of the gates and other buildings of the Royal Palace, after the earthquake of 1934. Moreover, on some stones, cement was also applied as a thin layer, probably in pursuit of fixing crumbling surface details.

3.3. The black layer

As mentioned at Chapter 2, at the beginning of the joint KVPT/ University of Applied Arts Vienna project in 2010, the carved panels of both the gates were covered with blackish layer of irregular thickness (Figures 5 and 6).
This coating was presumably applied in an earlier conservation campaign. Considering that cement layers are found over the black coating, it is probable that the coating was applied before the earthquake in 1934 or before the following reassembling when cement was used. However, it is still not known why this treatment was done. There are some hypotheses: either the coating is an aesthetical adaption to the dark painted wooden window and door frames (which were removed during the last years); or the coating was applied as a protection against the occurring biological colonization on stone surfaces, as a kind of hydrophobic layer to prevent water absorption. Neither archival data nor bibliographic references are available to evaluate these hypotheses. Moreover, no systematic investigation could be done to check whether other stone objects with similar coatings exist throughout the Kathmandu Valley. Only one gate on the west side of the Bhaktapur Palace with a similar coating is known to the authors, which was probably built at the beginning of the 18th century (Korn, W., 1976).

A sample of the black material was collected from one of the stone blocks of the Gate B (Southern) and was analyzed by FTIR (Nicolet 380 FTIR Spectrometer; Thermo Electron, USA). Part of the sample was analyzed directly without any preparation and another part after extraction with chloroform. The FTIR-ATR spectrum of the sample was compared with FTIR spectra databases of standards and with the spectrum of an aged bituminous adhesive collected from an element of the Karlskirche in Vienna. The best agreement was found with the spectrum of the bituminous material (Figures 7 and 8). According to the FTIR analyses, it could be assumed that the tested sample is with high probability, a bituminous material (tar, asphalt). A more precise determination (in terms of identification of the source materials for the bituminous substance) is not possible.

4. The cleaning

As mentioned in § 3.1, the material of the gates is rather highly absorptive. The simultaneous presence of water soluble salts and of the bitumen layer on the surface of all the carved parts makes the deterioration processes to happen even faster. Water, which penetrates into the stone matrix during rain, from the ground or during condensation events, cannot evaporate through this water repellent coating. The retention of water in the stone is also responsible for the intensity of the salt deterioration processes present at some stone parts. Water repellent surfaces are in favor of damages within the stone matrix. The presence of the water repellent layer prevents or slows down the evaporation of liquid water from the deeper layers of the stone and an evaporation zone may be formed behind the coating, where salts can crystallize as subflorescence and produce stress on the matrix (Charola A.E., 2000). The deterioration occurs in the stone and appears with flaking, scaling, peeling, etc. (Figure 9). In order to improve the stone condition it was therefore necessary to remove the bitumen layer and to reduce, as far as possible, the saline content.

The third aspect which had to be considered was the removal of the existing biological colonization. For this latter problem, the so called “Quats” (ammonium quaternary salts, namely Benzalkoniumchloride, by Merck®) solved in water (1:10) were directly poured on the stone surface and rubbed in with brushes.

![Figure 7. FTIR spectrum of sample from Gate B, after extraction in chloroform.](image1)

![Figure 8. FTIR spectrum of a historical bituminous adhesive, exterior stone elements of the Karlskirche, Vienna.](image2)
A reduction of salts in some stone parts was done by water bath. De-ionized water was not available in the worksite and rain water had to be used instead of tap water, as the latter resulted to be rather rich of chloride and nitrate ions, so not suitable for desalination purposes. Ordinary plastic buckets were filled with rain water and the stone blocks were fully immersed. The treatment was continued over several days, changing water when the salt content was too high. The performance of the salt extraction was frequently checked by the use of the colorimetric test stripes MquantTM by Merck®.

Finally, the problem of bitumen removal had to be solved. Different techniques were tried on stone fragments discarded during the reconstruction of the Gate by the KVPT. Organic solvents (ethanol, acetone, white spirits with different boiling points 60/95, 80/120, 100/140, 140/200 and ShellSol) were tested and compared, in combination with exposure to UV light or to IR (Figure 10). Also sandblasting was discussed at the beginning of the trials but this idea was abandoned for two main reasons: the intrinsic weakness of the damaged stone, which could result in appreciable loss of original surface and the very humid climate in Nepal during the monsoon, which could produce frequent block of the sandblasting nozzle. Notwithstanding the many solvents tested in different conditions, the results were rather unsatisfactory.

It was therefore decided to try the use of laser. A Nd-YAG Quantasystem Q-switch mode Laser with 1064 nm, 20 mJ, Medium Crystal was used for some preliminary tests. They were rather promising, even if the best operative conditions could not be defined. The problem, however, was a matter of sustainability more than a technical issue. In fact, no Laser equipment, suitable for stone cleaning, was available in Patan and it should have been imported from abroad. The Italian El.En. Group, one of the leading companies in the design, manufacture and distribution of high-tech laser sources and laser systems, was contacted and asked to support the project. El.En. generously accepted to offer one of their lasers for the summer campaign of 2013. Further preliminary tests were carried out in Florence to find the best equipment and the best operative conditions to obtain a satisfactory removal of bitumen, without any potential drawbacks for the stone surfaces.

Considering the conditions of the working site and the type of surfaces to clean, the modified Laser Eos 1000 LQS, working at $\lambda = 1064$ nm was selected as the most suitable equipment for the cleaning of the finely carved surfaces. Actually the optical fibre system for the beam delivery is lighter and handier for the operator. Moreover, thanks to the possibility of fine tuning of the operative parameters (i.e. Energy, Energy density, Frequency and Spot size), with LQS equipment the risk of photomechanical damage or discoloration is reduced. The efficiency and the graduality of the cleaning can be improved by the wetting of the stone surface with water. Together with the equipment, El.En. offered the assistance of an expert of the group who could organise a kind of “on the job training” for the Viennese team (who were already informed on the basic principles of the technique) on how to use the equipment and to manage it during the campaign.

The actual cleaning of the gate showed, as expected, differing results due to different conditions of the blocks. In areas with more or less intact, not weathered, surface the cleaning was very satisfactory, leaving only small rests of bitumen in the pores of the stone and an appealing patina.

Figure 9. Detail of peeling due to the bitumen surface.

Figure 10. Trials for reducing bitumen on a dismantled block.
Where the bitumen was applied to weathered surfaces the cleaning couldn’t be successful. Because of the weathering, the fabric of the stones was degraded, thus changing and probably increasing, the porosity of the stone. Therefore the bitumen was soaked deeper into the stone fabric (up to several mm) and encases the grains of the stone. This kind of deposition could not be removed without destroying the surface components. This is the case with the stones near to the ground, where the salt weathering produced the worst damages, but also for horizontal areas with direct impact of rain water. Moreover some blocks show layers of “weaker” composition due to sedimentation processes, where again weathering is increased. Last but not least, areas with rough surfaces – regularly to be found in undercuts where a smoothening of the surface was not possible are difficult to clean. Here the surface geometry is so complex that one cannot bring the laser beam in all necessary positions to remove the bitumen sufficiently. Despite all the difficulties, the laser cleaning can be called a success. Due to the possibility for a cleaning with selected intensity, the overall appearance of the gate was strongly improved (Figures 4, 11, 12 and 13).

5. Conclusions

The South Gate, after the reconstruction carried out in the 2012 campaign, needed to be cleaned, re-pointed where necessary, and esthetically harmonized. In order to reach this goal the following steps were implemented: Cleaning with acetone to remove the thicker incrustations of bitumen; Laser cleaning to remove the remaining bitumen without damaging the stone surface; Biocide treatment and pointing of cracked joints; Retouching of new stone reconstructions (darkening) in order to mitigate the color difference between the original stone and the new one. Partial retouching of areas where laser cleaning was not sufficient or effective; Retouching of joints. The laser technology, used for the first time on a Nepali monument, proved to be the key to solve a difficult and peculiar cleaning problem.
Acknowledgements

Univ.- Prof. Dr. Johannes Weber (Head of the Institute of Conservation Sciences at the University of Applied Arts Vienna) was the supervisor of the stone analytical test series. He also carried out the SEM/EDS analyses. The preparation of the thin sections was made by Dr. Andreas Wagner. The FTIR analyses were carried out by MSc. Karol Bayer (Institute of Conservation, University of Applied Arts Vienna). Mag. Art. Bettina Unterberger, freelance at the BDA (Austrian Federal Monuments Office), carried out the preliminary tests for Laser cleaning.

References

Experience of Conservation of Earthen Monuments in Kazakhstan

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Abstract

Tradition of building of earthen materials was widely spread over the territory of Kazakhstan; it is a result of the specific geomorphology of the country, where clays, loams and loess cover a good part of the area, especially in the valleys of such rivers as Syr-Darya, Talas, Chu. A lack of wood and stone made soils to be the most available material for construction in this area from the very early times of human civilizations up to the middle of 20th century. The history of earthen heritage in Kazakhstan was started in 1980, when at the institute “Kazproektrestavratiya” of the Ministry of Culture was opened a special laboratory for studies of historical and conservation materials. Laboratory provided conservators with materials research and recommendations for conservation of different kind of monuments. The first objects of its focus were Mausoleum of Khoja Ahmed Yasawi in Turkestan and archaeological monuments of Otrar oasis, where the main material of the medieval cities remains is the earth. A new wave of conservation of earthen structures was raised in 2001-2004 with implementation of the UNESCO/Japan Trust Fund and Kazakhstan for the conservation and restoration of Otrar-Tobe archaeological site – former large center of this oasis, very important for the functioning of the Silk Roads in the Middle Ages. At the same period in 2000s by the private company have been implemented several projects for conservation of vernacular architecture of nomads in the Central Kazakhstan. Mausoleums of 19-20th cc, standing in these wide steppe areas are the spectacular presentation of the unknown side of nomadic people culture. The article is an overview of some conservation projects implemented.

Keywords: Conservation, Kazakhstan, Earthen heritage, Nomadic
The history of conservation of earthen heritage in Kazakhstan was started in 1980s, when under the Ministry of Culture was established a scientific Institute "Kazprojektrestavratsiya". It consisted of different departments, working with different aspects of immovable cultural heritage preservation of the country: inventories, historical studies, conservation projects for heritage sites. In the same period there was organized a special scientific laboratory for regular and systematic research of historical building materials, providing recommendations for conservation and restoration projects.

Conservation activities of the institute from the beginning were focused on the most important heritage properties. Mausoleum of Khoja Ahmed Yassavi (dating from the 14-15th centuries) within archaeological landscape of ancient city of Turkestan and archaeological site of Otrar – a large medieval center on Syrdaria river were the main objects in this focus. A great number of excavated structures there were earthen and needed conservation, as they have been left under the open air pressures. So, the laboratory started to study materials from these medieval sites and experimented a lot with selection of conservation plasters and renderings, as well as with the methods of impregnation and treatment with modern materials.

In the period of 1980-s in the institute was gathered a very rich data on heritage properties over the country, including earthen ones. Expeditions to the remote steppe and desert areas discovered hundreds of very different and specific architectural and archaeological monuments. All of them were taken under the national protection.

Unfortunately, due to the crisis, which took place in 1990s following the crash of the Soviet Union – in the first years of independent Kazakhstan – nearly all research and conservation projects were stopped for a while. The next rise of heritage conservation – in general, and of the earthen heritage – in particular, started in the early 2000s. This coincided with the launch of the UNESCO/Japanese Funds-in-Trust Project for Preservation and restoration of the ancient city of Otrar (2001-2004) and of the State program "Revival of the ancient Otrar".

Archaeological site of Otrar, also known as the Otrar-toe, is a core of a large Otrar oasis, containing more than 230 heritage objects – remains of numerous small and large interconnected settlements. Otrar-toe was a very important center on the Silk Roads in the Middle Ages, it had a high influence on the processes of urbanization in this part of the trade routes. So, attention of the oasis researchers has always been focused at this site. The first excavations took place there in the early 20th century, then - in 1940s, and since 1970 they started to be permanent, in some years opening wide spaces. So, in general, to the beginning of 2000s have been opened about 7 hectares of the ancient city area on the level of 16-18th centuries’ layers, and some parts of the layers from Timurid (14-15 centuries) and Karakhanid (10-12 centuries) periods. Among the most interesting finds are remains of a bath dating from the 11and 15th centuries, quarter of potter artisans dating from the 13 and 14th centuries, brick-kilns dating from the 13 and 14th centuries, the Great mosque dating from the late 14th and early 18th centuries, fortifications dated by Karakhanid, Timurid and Kazakh Khanate periods.

Figure 1, 2. The archaeological site of Otrar-toe. General view (2011) and a view of the ruins of medieval mosques after conservation (2004).
In the main all of the excavated ruins are the structures, made of clay mortars and sundried bricks (on important public buildings – in combination with burnt brick). Being open to the severe natural air conditions of sharply continental climate, they are under the heavy pressure of a complex of negative natural factors and climate conditions. Such as, for example, combined effects of moisture, salts movement, extreme changes of temperature, winds, etc.

That is why the first conservation works started to be implemented on this site in the early 1980s, as soon as laboratory was established in the Institute Kazprojectrestavratziya. At the beginning they were mainly focused on the stabilizing of excavated remains of the Great mosque, made of burnt brick and clay mortars. In general this was a first step in the country in conservation of archaeological sites, and especially of earthen. So, the conservation activities were mainly related to the questions of water drainage, experiments with stabilization of different kinds of excavated earthen and mixed structures. In this time there were started the first regular studies on historical building materials.

When in 2001 the works for this highly important heritage site were renewed (thanks to the joint project UNESCO/Japanese Funds-in-Trust), they got a wide character with a long-term conservation strategy elaborated (Khorosh et al, 2005). In the process of the project realization were tested many different kinds of clay mortars and other materials for earthen structures conservation, was undertaken observation of behavior of the joint working of old and new materials after conservation applied. In some of the excavated places, like medieval residential areas, was done backfilling with the aim to prevent further degradation of fragile excavated earthen remains, standing without conservation for many decades. There was again paid a lot of attention to the organizing of a drainage system on the site to prevent excavated city structures from rain and snow waters with the help of special channels and vertical drains, waterproofing earthen ramparts. It is still functioning well. The conditions of conservation of the excavated remains were highly improved. What about the results of the mortars selection for the earthen structures coating of, they were not successful for many reasons, and one of them is that the soils on the site contain many salts, as well as all excavated structures. May be, another reason was in lack of research.

During this conservation project implementation, it appeared a need in emergency protection with a temporal cover for a piece of newly excavated city wall: to preserve it in winter for the next year excavations. By the advise of specialists of the Institute’s laboratory (V.Charlin and L.Charlina), it was made a coating with reed mats. This gave an excellent results, in spite of very heavy rains, snow, wind and temperature changes in the winter of that year. So, from this time this experience is introduced into the practice of temporal conservation of archaeological excavations. For example, on the excavated fragments of Otrar-tobe site such coating is used for several seasons, it provides a high level of preservation of earthen structures and surfaces.

Figure 3, 4. Archaeological site of Otrar-tobe. Protection with reed mats and a view of the ruins of medieval mosques after conservation (2004).

Another positive experience of the use of temporal shelters over excavations and structures under conservation during the UNESCO/Japanese Funds-in-Trust project gave an impetus to the development of shelters projects on
the site and on the other archaeological sites over the country. So, instead of temporal wooden shelter over the medieval bath ruins in 2009 was arranged a shelter with metal structure and curved form design.

![Figure 5, 6. Archaeological site of Otrar-tobe. Shelters over the ruins of medieval bath (2004 and 2011)](image)

Another permanent shelter with wooden structure was made over the ruins of medieval potter artisan’s workshops, where one of the buildings was reconstructed.

![Figure 7, 8. Archaeological site of Otrar-tobe. Views on the shelter over the ruins of medieval workshops of potter artisans with one building reconstructed (2011)](image)

Many tests on use of different conservation methods and mortars for arranging protective coverings were applied on excavated earthen ruins during this project realization. In the result of these experiments at present the most popular among restores is the variant, when original earthen structure is covered with sundried bricks by sides, covered by clay plaster on their surfaces. For plastering are used mortars with different additives, such as gypsum and lime. Instead of traditional straw often is used rice husk, because this often gives better conservation results and it doesn’t need special preparation. In the severe natural conditions of the territory where Otrar oasis is situated, this kind of plaster may have good state for about 2-3 years (if there are no extreme weather conditions).

Experience of use of clays from archaeological dumps for preparation of conservation materials on Otrar-tobe site showed, that water resistance of the mortars may be raised by lime additives, as they contain large amount of ash (including ash of reed), but at the same time, large quantity of soil in mortars reduces mechanical durability and increase water absorption. Therefore for preparation of conservation mortars and other materials in use is clay, taken from local clay quarries (Beisembaeva, 2011). It is necessary to note, that since the time of beginning of the UNESCO/Japanese Funds-in-Trust project, restoration and conservation works are going on the site continuously, but at present they are implemented by the State enterprise RGP Kazrestavratziya under the Ministry of Culture.
Another important earthen site which is under conservation by RGP Kazrestavratziya is a medieval cityAktobe\Balasagun. Its citadel was excavated in 1980s, and for a long was left without conservation and care, exposed to the impact from natural and climatic factors, like rains, salts, winds, high temperature differences, etc. It stands in the Chu river valley, on one of the main trade routes of the Silk Roads. Last scientific studies stated that once it has been a western capital of the Turkic Khanate (Shalekenov, 2009). Like many other large medieval cities it had a citadel surrounded by shahristan (political and administrative city center) and numerous rabads (suburbs with incorporated agrarian territories).

To the moment of the first conservation works on the site, started in 2009, excavated ruins were at a state of high degradation. It was necessary to start with archaeological cleaning of the walls remains to understand original planning and shapes of the ruins. After implemented cleaning on some of the buildings of the citadel complex, their earthen walls, made of brick and adobe, were restored to their original width (varied from 1 to 2,5m) with the help of sun-dried brick and clay mortar. The new surfaces were covered with clay mortar rendering. On their tops the walls were added with three layers of brickwork as a “sacrificial” layer. Then they were protected from the rain water by capping, made of clay mortar and reed mats. Over these layers was made a new layer of clay mortar with additives like gypsum and lime. To increase resistance of the capping against severe rains, which take place in this region last years, the last layer of clay mortar was made enriched with river stone of small sizes (up to 2 cm). To protect the walls in the foot from rains and snow, rising salts, was made covering with stone, as well as a drainage system for reducing water from the site was arranged. For the rendering mortars, made of clay, there were mainly used additives, such as gypsum and lime, experimented in different proportions. Also was used mortar with horse manure – traditional in this region, and the results of this traditional mortars may take a competition with those mentioned previously. Straw with the length of about 2 cm was usually added. But, unfortunately, at present, when every year we had extreme climate conditions with torrential rains and high level of snow in winter-spring season, it is not possible to say that the results achieved are successful: lack of conservation research and experimentation is very high (Turekulov, 2009-2012).

In parallel with conservation and restoration works, going on the large sites of the Silk Roads, having potential universal value, the beginning of 2000s is also marked as a start of conservation projects on the small earthen heritage properties. They were mainly concentrated in the Central Kazakhstan and realized by a team of the first in the country private conservation firm “Kumbez”. The projects were highly supported by the local administration and local communities. The first of them was conservation of archaeological remains of the medieval settlement Baskamyr, located on one of the routes, connecting Ulytau oasis and its rich copper mining centers with the main routes of the Silk Roads.
Archaeological excavations took place there in 1990s and they opened remains of adobe structures of the walls of fortified settlement, with houses, service buildings, defensive walls, system of signal towers. First of all the authors of conservation project started to decide the questions of water drainage. For the walls preservation was selected a method of their conservation with clay mortar rendering over original surfaces. The walls were cleaned and special synthetic net for plaster reinforcing was arranged with the help of wooden nails. In preparation of the clay mortars was used soil from archaeological dumps, and up to 30% of horse manure was added into the mortar. The walls were covered with mortar manually. This method and the mortar itself, used on this site, is working quite well till now, in spite of the severe climate and natural conditions, and in spite of the fact, that since that time no any of maintaining works was applied. Only the parts of plaster in the foot of the walls are a subject to erosion, and they are concentrated mainly in the places where snow remains for a long in spring.

At the same time on the edge of 20-21th cc. the first conservation works were implemented by this firm on the architectural monuments in the Central Kazakhstan. It is necessary to note, that numerous mausoleums, built of earthen materials in the period of the end of 19th – beginning 20th centuries in remote from the cities steppe areas, at present are in a critical point of their technical condition. They are a unique presentation of vernacular architecture of nomadic people. More than 100 years they didn’t have any maintenance, what was connected with disappearing of private ownership on lands and livestock in the Soviet Union, as well as with intensive processes of urbanization, destroyed traditional nomadic and semi-nomadic way of life, traditional for Kazakh people. In 1980 expeditions studied this heritage in steppes of the Central Kazakhstan and determined that urgent conservation works should be implemented on the most of these earthen structures to prevent them from collapse. Destructions on these heritage properties will mean disappearing of the very important part of the national heritage, of the heritage of nomadic culture in general (Turekulov, 1987).

**Figure 11.** Medieval settlement Baskamyr, Ulytau oasis in Central Kazakhstan. General view (2007)

**Figure 12, 13.** The mausoleum of Ali-Tusup before and after the emergency conservation, Central Kazakhstan. General views (2004 and 2007)
Analyses of destructions on the mausoleums detected that the most dangerous of them are structural cracks, erosion from the wind and rains on the domes top, roof, in the foot of the walls. Often the most dangerous are missing parts, small at the beginning, but promising collapse of wide structures, like, for example, on the arches or in the corners of a dome’s basement.

So, the main emergency conservation works on these earthen structures are: restoration of roofs and organizing of water draining, restoration of missed elements and structural elements close to collapse, restoration of the walls’ eroded surfaces in the basement, organization of water drainage on the ground. Thanks to realization of a number of such projects of emergency conservation and restoration in the Central Kazakhstan some of them were saved.

In conclusion it is necessary to note, that earthen heritage is a significant and very diverse part of the whole cultural heritage of Kazakhstan. At the same time it is the most fragile from the point of preservation. So, the task of its conservation is very important nowadays, considering many excavated earthen sites over the country, and many examples of earthen vernacular architecture located in the remote steppe and desert areas. In practice conservators are faced with many complicated problems, and it is extremely important to work in cooperation with experts from different fields and conduct complex interdisciplinary research, to learn international experience.

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Photos by the author
Conservation of Historic Lime Plaster on Earthen Heritage: A Case Study of Liu’s Family Ancestral Hall in Jinggangshan, Jiangxi

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Abstract

Earth is the oldest building material which is still used widely nowadays. Earthen architectural heritage has important values in aspect of history, art, technology and ecological sustainability. Liu’s Family Ancestral Hall, erected in 1824, in Jinggangshan is one of these representatives. The rammed earth wall was plastered with two layers of lime plaster, of which the composition has been chemically and mineralogically analyzed. The conservation principles have been proposed after documenting the typical defects of the rammed earth wall and related plaster. Based on the comprehensive studies in laboratory, conservation concept inclusive surface consolidation with ethyl silicate, refitting and crack injection with NHL grout, cleaning and restoration of the slogan characters have been worked out. This concept has been implemented on the conservation site and shall function as model for future restoration and conservation.

Keywords: Earthen architectural heritage, Liu’s Family Ancestral Hall, Deterioration, Conservation, Lime plaster

1. Earthen architectural heritage: Liu’s Family Ancestral Hall

There are lots of revolutionary resources preserved in Jinggangshan region of Jiangxi Province. Liu’s Family Ancestral Hall (Figure 1), which was built in 1824 according to Liu’s Genealogy, is one of these representatives. Most of heritages in this area are traditional earthen-timber architectures (Figure 2), reflecting vernacular cultures and conveying precious memories of history period. Liu’s Family Ancestral Hall has been listed as Heritage protection unit of Jinggangshan city, but it is not in a good protected condition now. Has experienced winds and rains for almost 200 years, this heritage is suffering different degrees of damages due to natural and human factors. It is urgent to take appropriate rescue measurements to prolong the life of this treasure.

Figure 1. Liu’s Family Ancestral Hall.
Figure 2. Traditional earthen-timber architecture.
2. Values assessment and focus of conservation

Liu’s Family Ancestral Hall has important values of history, art, technology, economy and ecological sustainability. It embodies regional and vernacular features in aspect of the building form, construction material and technology. The building has earthen-timber structure and overhanging gable roof. It consists of a main room, two side rooms and five patios with an overall area of 520m². The main room which is 21m wide and 25m deep is constructed with 14 wooden columns and rammed earth wall as load-bearing components. Rammed earth wall (Figure 3), which is called “Gandalei” by locals, is built by stamping earth and gravel between board frames. And it has been said that raw Tungoil, a kind of natural oil from tree nut in South China, was mixed into earth and lime mixture as damp proofing barrier. No organic remains, however, have been identified in the samples taken from the basements and floors. It has been proven in the laboratory that Tungoil has the capability to enhance the strength, freeze-thaw resistance and wet-dry resistance of construction materials. In addition, there are some pebbles in basement and wood twig reinforcements (50mm in diameter) (Figure 4) in rammed earth wall increasing the stability and rigidity.

![Figure 3](image3.png) Cross section of the earthen construction.  
![Figure 4](image4.png) Wood twig (sometimes bamboos) reinforcements in rammed earth wall.

The protective lime plaster of the earthen wall was constructed in two layers: The base coat is a lime mortar consisting of 15wt% lime, 20wt% earth, 30wt% sliver sand and 35wt% coarse sand, while the top layer is pure lime with small amount cotton fiber as reinforcement.

In the early of 1930s, the Red Army painted a lot of revolutionary slogans on the walls of Liu’s Family Ancestral Hall (Figure 5). It is should be regarded as a kind of historical data and document, which recorded the stories in the past and recalled memories of particular ages. Also it is the most important factor which makes this building different from others. So we should put the focus on preserving these valuable slogans, including rammed earth walls and the lime plaster, without which the slogans would not be exist anymore.

On the other hand, ancestral hall is one of the most important primary traditional architecture types in China. It is a place for ancestor worship, weeding, funeral, celebration, family meeting, public activity and communication and so on. What’s more, Liu’s Family Ancestral Hall is one of the red-cultural material resources, which has potential value of tourism development and education.
3. Conservation principles and existing modes

Based on the field investigation and comprehensive studies on Liu’s Family Ancestral Hall, following principles are proposed for future research and development works.

**Emergency repair**: as priority to take any possible and effective measures to rescue and safeguard the most valuable slogans on site, avoiding further destructive deterioration of the building. **Integrity**: the architectural should be considered as a whole organism, which means the columns and beams are bones of the building, the rammed earth wall is flesh, the lime plaster is skin, the slogans are fur, and the roof is coat. These elements are correlative with each other and have non-negligible interactions. **Authenticity**: restoration should follow original style with original construction material and craft as far as possible. But it doesn’t mean that we reject all new material and technique, only if they are beneficial to the heritage. **Distinguishability**: the restoration part should be distinguishable from the old one, and coexist harmoniously. **Reliability**: the developed materials and introduced technology should be safe, reliable, economically affordable and sustainable.

To Liu’s Family Ancestral Hall, which is relatively kept intact, it’s better to conserve on site with the basis of adequate experiments and tests according to above conservation principles. We should draw lessons from previous failures and defects, improving preservation materials and developing a scientific and feasible technical route.

4. Conservation materials and technologies

4.1. Restoration and consolidation of rammed earth wall

Repairing the rammed earth wall is a crucial step for conserving the valuable slogans. There are many apparent cracks and man-made holes in the west and east facade. Locals had ever restored the back wall of the main room with improper bricks. After littery stones and concrete bricks filled in man-made holes for doors or windows had been removed, we rammed the earth wall as original style with original materials, pebbles, earth, sands, lime and Tungoil were mixed and rammed using historical instruments and craft (Figure 6).

For the surface consolidation of the old earth, various methods were tested in the laboratory (Figure 7). The parent earth was sieved and rammed onto stainless steel basin, after air dry for approx 28 days, the lime plaster fragment collected from the Liu’s Family Ancestral Hall were adhered to the earth surface using a lime-based adhesive. The cracks occurred during the dry process of the rammed earth were injected with 2 earth injection grouts based on natural hydraulic lime ((NHL, mixed with water) and micro lime (mixed with ethanol). After curing for approx 7 days, the 50% of the earth surface was flooded with pure ethyl silicate, 50% was flooded
with ethanol-based micro lime. The treated samples were optically documented and cured for 7 days and then artificially rained, the resistance of treated earth and adhesion of the refitted lime plaster were documented. The results showed that pure ethyl silicate is better than water-free micro-lime in aspect of reinforcing the rammed earth; the mixture of natural hydraulic lime and earth has lower shrinkage and can be used as injection grout for refitting and crack filling. However the adhesion between the lime-based injection grouts and old earth materials after carbonation will be further tested.

4.2. Delamination and injection filling

The defects of hollowings on the walls have been tested and documented by drilling resistance measurement system (DRMS). The hollows are located app. 5mm beneath the surface (Figure 8) and between lime plaster and earth. The most relevant conservation effort is to refit those delaminated plaster. The technical requirements for the grout are compatible both with lime plaster and earth, besides it shall water absorbed, water vapor permeable. Based on the feasibility tests, the mixture of modified natural hydraulic lime (NHL) and fine earth has been selected, the mixture ratio of NHL and fine earth ranges from 1:0 – 1:1 in weight depending on the dimension of hollow space. The workability of such grout was satisfied (Figure 9) and the effectiveness will be investigated after the completion of the hardening.

4.3. Restoration of revolutionary slogans

The revolutionary slogans on the walls are focus of preservation project for their significance of history and
memory, but they became blurred because of colors fading and losing. The microscopic research has proven that the slogans were written in ash from the bottom of iron pans with barks (Figure 10) as locals told. The coarse black pigments were found on top of lime layer, almost without any visible binders. The fading is mostly caused by weak adhesion of pigment, not by color changing. New black restoration lacquer mixed with Tungoil and ash (Figure 11) has been formulated and will be applied to restore the slogans.

5. Conclusions

Liu’s Family Ancestral Hall is one of the most typical earthen-timber heritages, which has important values and deserves preservation. When conserving it, doing lots of precise tests and verifiable experiments is the precondition and foundation. Principles inclusive emergency repair, integrality, authenticity, distinguishability and reliable should be followed strictly (Figure 12). It is very necessary to introduce new material and technology to restore the heritage better, at the same time the original low-technology should be taken seriously for its economical and ecological efficiency. The tests which achieved good results shall function as model for future restoration in Jinggangshan region.

**Figure 10.** Microscopic investigation proving as the saying is correct.

**Figure 11.** Collection of ash on the bottom of iron pan pigments.

**Figure 12.** Restoration process during December 2013, the façade was partly restored.
Acknowledgements

This article is completed under the financial support of China National “Twelfth Five Years” Key Research and Development Project granted No. 2012BAC11B01-2, the Architecture Conservation Laboratory (part of the Key Laboratory of Ecology and Energy-saving Study of Dense Habitat, Tongji University, Ministry of Education, PR China). The authors thank Zhu Shangyou, Zhou Yuee, Chen Lin, Chen Guojun for helping of the laboratory testing and mock-ups in collaboration with Shanghai DS Building Materials Co. Ltd.. The authors express deep appreciation to other members of research team from Jinggangshan University and staff of Jinggangshan Museum for sharing data and achievement in different fields. The authors also acknowledge locals in Shangqi Village for good cooperation and reception.

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Yungang Cave 9, 10 Column Weathering Degree of Environmental Magnetic Non-destructive Evaluation

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Abstract

The degree of weathering of rocks, quantitative evaluation and non-destructive detection, is the premise and the requirements of governance stone relics weathering disease. On the basis of qualitative observation, the use of environmental magnetism portable magnetic susceptibility meter on-site degree of weathering weathered sandstone of the Yungang Grottoes nondestructive proposed the quantitative grading standards of the Yungang Grottoes sheet weathered sandstone degree of weathering, and to Yungang 9,10 Cave east colonnade object quantitative evaluation of the practice of the degree of weathering. That the Yungang Grottoes sheet weathered sandstone weathering degree is divided into 5: average fresh in coarse sandstone susceptibility of $0.056 \times 10^{-6}$ SI; weak weathered sandstone susceptibility Mean ($\mu$) of $0.051 \times 10^{-6}$ SI, the range of $0.035 \sim 0.066 \times 10^{-6}$ SI; moderately weathered sandstone susceptibility Mean ($\mu$) of $0.099 \times 10^{-6}$ SI, the range of $0.086 \sim 0.121 \times 10^{-6}$ SI; strongly weathered sandstone susceptibility Mean ($\mu$) of $0.082 \times 10^{-6}$ SI the range of $0.066$ to $0.086 \times 10^{-6}$ SI; whole weathered sandstone susceptibility Mean ($\mu$) of $0.060 \times 10^{-6}$ SI range of $0.044 \sim 0.070 \times 10^{-6}$ SI. Yungang Grottoes sheet weathered sandstone magnetic susceptibility values in the process of weathering retreat quality characteristics first and then decreased. Cylinder the Yungang first 9,10 Cave East colonnade toward the control of the degree of weathering of sandstone north minimum degree of weathering, is moderately weathered the east, westerly degree of strongly weathered south degree of weathering, is a full weathering. Mainly affected by the influence of solar radiation and rain erosion directly. Restore the construction of a protective cave eaves is the delay of the Yungang the first 9, 10 Cave column column weathering the most effective way.

Keywords: Yungang Grottoes, Degree of weathering, Environmental magnetism, Non-destructive detection

1. Introduction

The evaluation of weathering degree is the premise for solving the weathering disease of stone relics. On the international, most relative criterions and regulations used qualitatively descriptive method of macroscopic geophysical characteristics to divide the degrees of weathering stones in engineering field. For the lack of quantitative guidelines, the criterions are not easy to be carried out. In 1970s, the researchers began to use the guidelines of stone microscopic features (Hamrol, 1961; Hu et al, 2005; Shang and Wu, 2001; Shang et al., 2004), the features of physical mechanics (Cheng et al., 1999; Wei, 1982; Xiang, 1985) and the changes of the chemical composition of minerals (Cheng et al. 2008; Qu and Wu, 2000; Song and Peng, 2002) to do quantitative classification. Although these guidelines are taken as the dividing criterions of stones’ weathering degree and have prompted the division of weathering stones degrees to develop in quantitative field, those guidelines are not able to be detected in time and some sampling work may make damage on relics, so they are difficult to be popularized and adopted in actual protecting projects of stone relics.

Environmental magnetic, a new scientific subject related to the geological science, environmental science and magnetic science, developed from 1980s. Its main aim is to explode the rules of transfer, transformation and combination of magnetic minerals in environmental system by studying magnetic characteristics of environmental materials, then to research the environmental problems, the mechanism of environmental procedures and their effects during different spatial and temporal scales by utilizing the relationships of magnetic materials and the environmental meanings they reflected (Evans and Heller, 2003; Thompson and
Oldfield, 1986). The magnetic susceptibility of magnetic parameter is one physical quantity to show the magnetic intensities of stones. It is mainly used to study pedology (Maher, 1986; Yun et al., 1991), the changes of ancient climates and environments (Heller and Liu, 1986), the influence of human activities and environmental pollutions (Hunt, 1986; Lu et al., 2001; Luo et al., 2000; Versteeg et al., 1995). In recent years, it has been applied to study weathering subjects of stones (Lang et al., 2011; Xun et al., 2004). However, it is rare to use portable magnetic susceptibility meters to do on-site non-destructive detection on weathering degrees. Based on qualitative observations, the aim of the study is to use portable magnetic susceptibility meters to do non-destructive detection the columns in Cave 9, 10 of Yungang grottoes and do research on evaluation of weathering degrees by analyzing the magnetic characteristics of these columns. The study is able to provide scientific basis for remedying the weathering diseases of Cave 9, 10 and formulating appropriate protecting measurements.

2. The general situation of Yungang Cave 9, 10 and the climate of research area

Yungang Grottoes, one of the most three bigger grottoes in China, represents the Chinese outstanding Buddhist grotto art between the 5th century and the 6th century. It is the classic masterpiece of the first peak of Chinese Buddhist art. The Cave 9, 10 is a pair of caves which are built in A.D. 484 and designed by Wang Yu, who is one of the eunuchs of queen mother Feng. There are two octagonal columns in front of each cave. They kept the Chinese architecture style of ancient Han and Wei dynasty, named as “Jin kan qi lie, yu ju cheng ba”, which means the golden columns are parallel arranged and based on the jade plinths. The carven style of them is similar to the temple’s column style with obvious Indian style and even some Greek and Roman architecture style. They are the intercommunication and syncretism model between Chinese culture and Western culture at that time. The columns are outdoor stone columns with the thick bottom and the thin top approaching the top of the colonnades. There are ten layers of Buddha statues on every surface of the columns. The bottom part is an elephant style column basis and a Sumeru throne on the back of the elephant. The statues on the north surface are protected in good condition, and the statues on the south cylindrical surface are all weathered. The partial statues on the east and west cylindrical surfaces and the elephants’ head are all weathered too. They are not able to show the wealthy and splendid scene as that time any more. The weathering diseases are mainly in the flaky forms. Some of the statues are shelled and even exfoliated (Figures 1 and 2).

Figure 1. Yungang Cave 9 and Cave 10 columns.
Yungang Grottoes area belongs to the temperate continental half-arid climate with the annual average temperature of 7-10 °C. January is the coldest time of one year with the average temperature of -11.4 °C and July is the hottest time with the average temperature of 23.1 °C. The annual average precipitation is 432.8mm and the rain season concentrates on July to September, when the top precipitation is more than 100mm. The annual evaporation is 1748mm and the biggest evaporation time is June with 801.8mm, and the smallest evaporation time is December with 74.9mm. The annual snow cover is about 20mm. The freezing period is from the end of October to the next April with average freezing depth of 1.5m. The annual foist-free period is about 120 days.

3. The dividing criterion of stones weathering degrees in Environmental magnetic

3.1. Theoretical basis

The rock magnetism is mainly caused by the magnetic iron materials in the rock. The energy spectrum analysis of Energy Disperse X-ray Detector shows that the new sandstone in Yungang Grottoes contains plentiful iron elements. The tests of chemical elements of new and weathered sandstone with different depths show that the components and contents of iron oxide vary in different weathered sandstones with various depths (Huang, 1984). The sandstones in Yungang Grottoes have being weathered all the time accompanied with the formation and transformation of iron oxide and ironic hydroxide (Huang, 2006).

3.2. SM-30 portable magnetic susceptibility meter

The on-site measuring instrument is SM-30 portable magnetic susceptibility meter made in Czech showed in Figure 3. It is widely used in geology and geography. It has a high sensitivity of $1 \times 10^{-7}$ SI and can accurately detectable the susceptibility of paramagnetic, ferromagnetic and diamagnetic rocks. Its volume is only 100×65×25 mm and its weight is 180g. It has six measuring models. Its sensor’s diameter is 50mm and can obtain the 90% signals during the scope of 20mm. It can be adjusted to do measurement. It is easy to operate. After switch it on, the accurate measuring data can be detected and showed on the screen in several seconds by the sophisticated signal processing system. And it can reduce the influence from outside electromagnetic interference and electronic equipment. It is the ideal non-destructive detector in the wild field with its characteristics of small volume, light weight, speedy detection, low cost and non-destructive influence.

Figure 2. The south, east-west, north cylindrical surface of Yungang Cave 9, 10 column.
3.3. The criterion of quantitatively dividing degrees

Yungang Grottoes are carved on the sand lens of the top Yungang group of the Middle Jurassic (Bureau of Geology and Mineral Resources of Shanxi Province Third Comprehensive Survey Company, 1990). The main rock is the coarse grained feldspar quartz sandstone. On the basis of previous researchers (Mo et al., 2000), combining with the actual situation of weathered sandstones in Yungang Grottoes and according to the colors of weathered sandstones, changes of stones’ organization structures and crushing situation, changes of mineral components, characteristics in physics and chemistry, and the sound of hammering, the sandstones are divided into five kinds: fresh sandstones, weak weathered sandstones, moderately weathered sandstones, strongly weathered sandstones and whole weathered sandstones. The SM-30 portable magnetic susceptibility meter had been used to test the fresh coarse sandstones and sheet weathered sandstones. The measuring data were analyzed by the Excel files (Excel 2003). In Figure 4, the susceptibility frequency distribution curves of sheet weathered sandstones with various weathered degrees are all skewed normal distribution. According to the fact that the percentage of existent data during the region of (,) is 95.4% and the values of the intersecting points of the adjacent distribution curves, the sheet weathered sandstones are divided into several kinds by their weathered degrees. The results are showed in Table 1.

It can be seen that: (1) the average susceptibility (μ) of Yungang fresh coarse sandstone is 0.056 × 10^{-6}SI; (2) weak weathered sandstone μ is 0.051 × 10^{-6}SI, the range of standard deviation (σ) is 0.035 ~ 0.066 × 10^{-6}SI; (3) moderately weathered sandstone μ is 0.099 × 10^{-6}SI, σ is 0.086 ~ 0.121 × 10^{-6}SI; (4) strongly weathered sandstone μ is 0.082 × 10^{-6}SI, σ is 0.066 to 0.086 × 10^{-6}SI; (5) whole weathered sandstone μ is 0.060 × 10^{-6}SI, σ is 0.044 ~ 0.070 × 10^{-6}SI. Generally speaking, during the weathering process of sheet weathered sandstones in Yungang Grottoes, the susceptibility has the rule that first increase and then decrease. The trend is that: low susceptibility in the weak weathered period, the highest susceptibility in the moderately weathered period, high susceptibility in the strongly weathered period (less low than that in the moderately weathered period), the lowest susceptibility in the whole weathered period.

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<th>Weathered degrees</th>
<th>Average (μ) (10^{-6} SI)</th>
<th>Valid range (10^{-6} SI)</th>
<th>Standard deviation (σ) (10^{-6} SI)</th>
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<td>0.056</td>
<td></td>
<td></td>
<td>0.107</td>
<td>0.004</td>
<td>287</td>
</tr>
<tr>
<td>Weak Weathered</td>
<td>0.051</td>
<td>0.035</td>
<td>0.066</td>
<td>0.117</td>
<td>0.005</td>
<td>140</td>
</tr>
<tr>
<td>Moderately Weathered</td>
<td>0.099</td>
<td>0.086</td>
<td>0.121</td>
<td>0.196</td>
<td>0.056</td>
<td>503</td>
</tr>
<tr>
<td>Strongly Weathered</td>
<td>0.082</td>
<td>0.066</td>
<td>0.086</td>
<td>0.154</td>
<td>0.025</td>
<td>540</td>
</tr>
<tr>
<td>Whole Weathered</td>
<td>0.060</td>
<td>0.044</td>
<td>0.070</td>
<td>0.097</td>
<td>0.016</td>
<td>325</td>
</tr>
</tbody>
</table>
4. The environmental magnetic and non-destructive evaluation for the weathered degrees of the east columns in Yungang Cave 9, 10

The on-site measuring location for the east columns of Yungang Cave 9 and 10 selected at 2 meters above the floor, they are relatively plain for the measurement. The Zero start point is located at the west-north corner. The soft leather ruler was used to round the column for one circle and fixed by wooden clamps when strained to index the location of measuring points. The SM-30 portable susceptibility meter was used to measure the data every 3cm for one circle along the anticlockwise direction: west south east north. The measuring data are stored in Excel files and the susceptibility-location curve charts are generated.

4.1. The characteristics of non-destructive susceptibility for the east column of Yungang Cave 9

It can be seen from Figure 5 that the magnetic susceptibility’s variability of the east and west cylindrical surfaces are varied range greatness and that of the south and north cylindrical surfaces are steady, but the magnetic susceptibility of the north cylindrical surface is higher than that of the south cylindrical surface. According to the dividing degrees of sheet weathered sandstones in Yungang Grottoes showed in Table 1, the weathering situation of every cylindrical surface of columns in Cave 9 are: (1) the range of magnetic susceptibility of the west cylindrical surface is 0.05~0.117×10^{-6}SI; (2) the range of magnetic susceptibility of the south cylindrical surface is 0.05~0.074×10^{-6}SI; (3) the magnetic susceptibility of the east cylindrical surface have several anomalies because some measuring points just locate at the reinforced cracks, except the abnormal points, the range of the magnetic susceptibility is 0.058~0.117×10^{-6}SI, it is the strongly weathered sandstone with the average magnetic susceptibility of 0.085×10^{-6}SI; (4) the range of magnetic susceptibility of the south cylindrical surface is 0.089~0.124×10^{-6}SI, its average is 0.1053×10^{-6}SI referred to the moderately weathered sandstone.

![Figure 5. Yungang Cave 9 east column non-destructive testing magnetic susceptibility values curve.](image-url)
4.2. The non-destructive magnetic susceptibility characteristics of the east column in Yungang Cave 10

It can be seen in Figure 6 that several magnetic susceptibility values is bigger than 0.2×10^{-6} SI, just because the measurement points located at the reinforced cracks. When the abnormal points were eliminated, the curve chart in Figure 6 changed to that in Figure 7. In Figure 7, the east and west magnetic susceptibility variation of the east column in Cave 10 is much bigger than that of the south and north cylindrical surfaces, where the value is smooth and have no big fluctuation. The north one is bigger than the south one. The weathered situation of the east column in Cave 10 are: (1) the range of the west magnetic susceptibility is 0.058~0.122×10^{-6} SI with the average value of 0.0815×10^{-6} SI indicating the strongly weathered sandstones; (2) the range of the south magnetic susceptibility is 0.053~0.071×10^{-6} SI with the average value of 0.0623×10^{-6} SI indicating the whole weathered sandstones; (3) the range of the east magnetic susceptibility is 0.065~0.123×10^{-6} SI with the average value of 0.084×10^{-6} SI indicating the strongly weathered sandstones; (4) the range of the north magnetic susceptibility is 0.092~0.168×10^{-6} SI with the average value of 0.1158×10^{-6} SI indicating the moderately weathered sandstones.

It can be seen in Table 2 that the weathered degrees in various cylindrical surfaces have large difference and the sandstones in the same orientation have the same weathered degrees. The magnetic susceptibility in the north orientation, in contrast, is less small with the moderately weathered degree. Strongly weathered sandstones are in the east and west orientation. The most weathered sandstones are in the south orientation; their weathered degrees are the biggest. So the order of the weathered degree from strong to weak is that: n_{south}=n_{east}>n_{north}>n_{west}.

![Figure 6. Yungang Cave 9 east column non-destructive testing magnetic susceptibility values curve.](image1)

![Figure 7. Yungang Cave 10 east column non-destructive testing denoising magnetic susceptibility values curve.](image2)

<table>
<thead>
<tr>
<th>Name</th>
<th>Forward</th>
<th>Average (10^{-6} SI)</th>
<th>Maximum (10^{-6} SI)</th>
<th>Minimum (10^{-6} SI)</th>
<th>Weathered degree</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>The east column in Cave 9</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West</td>
<td></td>
<td>0.083067</td>
<td>0.117</td>
<td>0.05</td>
<td>Strong</td>
</tr>
<tr>
<td>South</td>
<td></td>
<td>0.062929</td>
<td>0.074</td>
<td>0.05</td>
<td>Whole</td>
</tr>
<tr>
<td>East</td>
<td></td>
<td>0.085</td>
<td>0.117</td>
<td>0.058</td>
<td>Strong</td>
</tr>
<tr>
<td>North</td>
<td></td>
<td>0.105346</td>
<td>0.124</td>
<td>0.089</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>The east column in Cave 10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West</td>
<td></td>
<td>0.0815</td>
<td>0.122</td>
<td>0.058</td>
<td>Strong</td>
</tr>
<tr>
<td>South</td>
<td></td>
<td>0.06225</td>
<td>0.071</td>
<td>0.053</td>
<td>Whole</td>
</tr>
<tr>
<td>East</td>
<td></td>
<td>0.084</td>
<td>0.123</td>
<td>0.065</td>
<td>Strong</td>
</tr>
<tr>
<td>North</td>
<td></td>
<td>0.115833</td>
<td>0.168</td>
<td>0.092</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
4.3. Results and analysis

SM-30 portable magnetic instrument can also evaluate weathering degree for about 2 cm beneath the rock surface compared with the ultrasonic testing (Sun et al., 2006) which is the traditional technique for testing the weathering degree of surfaces of stone relics. The SM-30 have high precision, and can directly read data and intuitive assessment at the scene, as well as can avoid the unnecessary pollution due to the use of coupling agent on cultural relics. It is feasible to nondestructive evaluation of sandstone weathering degree use of SM-30. It can provide reliable basic data for the protector of stone lice, and has important reference value.

It is founded weathering degree of the sandstone are largely decided by the orientation, through the study of the weathered degree of the colonnade at Yungang Grottoes cave 9 and 10. The influence of sandstone weathering is their character (such as the structure, composition and content of the rock, cement type, etc.) and weathered environment (such as sunlight, wind, precipitation, and harmful gas from the atmosphere, etc.). The weathered degree of the same kind rock is mainly controlled by the environment, while for the Yungang Grottoes which locate on the semi-arid environment, the weathering degree of the east colonnade in Yungang Grottoes cave 9 and 10 are mainly controlled by solar radiation and rain wash directly, and the degree of solar radiation and rain wash decided by orientation. In general, the colonnade toward the north influenced by the solar radiation and rain wash directly below the other direction.

Rock is composed of a variety of mineral composition, and the thermal expansion coefficient of each mineral is different. The thermal stress of rock is generated from temperature difference, and the connection between the rock particles can be destroyed when the thermal stress achieves a certain level. As a result, the weathering degree of the south, east and west of the rocks are bigger. As well as, the weathered rock caused by thermal stress and often showed flaky exfoliation same as the field observed result (Sun et al., 2006). In addition, the dry-wet circulation and salting out weathered of sandstone are occurred more frequency for located on the south, east and west (Turkington and Paradise, 2005).

The directly rain washing column not only make the loose rock particles and cutting body off which result mechanical erosion along the fracture, but also make the mud on the stone wet and soften which result the rock cementation force falling and the large weathered layer falls off, eventually lead to the volume expansion of rock mass, even burst. Yungang grottoes total rainfall is 115.1 mm in July 2003, the weathering sand of two colonnades No.9 were 739.2 g and 490.0 g separately. Distribution around Yungang Grottoes many coal mines and the living area, release huge containing SO$_2$, NO$_2$, NH$_4^+$ and F $-$ gaseous pollutants in production and life. The SO$_2$, NO$_2$ to react with H$_2$O can oxidized to SO$_4^{2-}$, NO$_3^-$ that make the area of rain (snow) water complex composition and pH became acidic, which has strong corrosion for Yungang Grottoes (Huang, 2006). Under thousands of years of rain washing, the columns were weathering damage accumulation, which inevitably cause the colonnades instability and endanger the cave safety.

Since the Northern Wei dynasty, the ancient ancestors have realized the influence of direct solar radiation and rain erosion for the grottoes. There are still residual stone ruins of eaves on the top of cave 13. The eaves and wood structure of Liao Dynasty "ten temple" and the Qing Dynasty of cave 5, 6, 7 and 8, have played a certain protective function to the grottoes. In addition, the eaves plays a role in isolating sand, keeping the temperature relatively stable, therefore, it is the most effective method to delay the colonnades weathering to build eaves for the cave 9 and 10 of Yungang Grottoes (Huang, 1984).

5. Conclusion

(1) The portable SM-30 magnetic susceptibility instrument of environmental magnetism was used for nondestructive evaluation of sandstone weathering degree is feasible. And that can provide basic data for the stone protector formulating reasonable prevention measures. So there is important scientific significance.

(2) The weathering degree of Yungang Grottoes sheet sandstone is divided into 5 levels, and their characteristics of magnetic susceptibility is increased before they are reduced during the process of weathered
metamorphic.

(3) The weathering degree of the east colonnade in Yungang Grottoes Cave 9 and 10 measurement zone are same for the same orientation while have bigger difference for the different orientation. The weathering degree of north colonnade is the weakest and belongs to the moderately weathered; by comparison, other orientations of the colonnade are strong and belong to the strong weathered, especially the south of the colonnade is the strongest.

(4) Under the action of local weathering environment, the weathering degree of the colonnade in Yungang Grottoes cave 9 and 10 are controlled by their orientations: \( n_{\text{south}} > n_{\text{west}} = n_{\text{east}} > n_{\text{north}} \).

(5) The main external factor of the weathering degree of the colonnade in Yungang Grottoes cave 9 and 10 is sun exposure and rain erosion.

(6) The most effective way of slowing down weathered for the colonnade in Yungang Grottoes cave 9 and 10 is to build protective eaves which can reduce the directly external affects for colonnade.

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The Study on Crack and Tilt Deformation of the Brick Shrines at Sambor Prei Kuk

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Abstract
To understand the wall deformation on the Khmer brick shrines, an adaptable method on the field for checking the wall conditions is set and applied on Sambor Prei Kuk ruins in Cambodia. Through the result and additional analysis, the deformation of walls of Khmer brick shrines is classified.

Keywords: Khmer temples, Restoration, Brick, Crack, Tilt deformation

1. Introduction

During the 7th to 10th century, the Khmer built lots of religious buildings using burned bricks. The most of brick buildings deep in the dense forest have been damaged by weathering over a thousand years. The damaging has been made by complicated and various reasons, but mostly by the collapse which caused significant change of the buildings itself. It is impossible to restore the brick construction after the collapse because it has been changed like clod of clay through the years.

Cracks are occurred by ‘foundation uneven movement’, ‘original structure problem’, ‘external shock’, ‘thermal movement and moisture uptake or loss’, ‘external loads’, ‘growth of excessive vegetation’, etc. And the various displacement aspect of construction has been appeared until collapse. The research is aimed to analyze cracks and tilt deformation of the buildings to categorize the cause of collapse and condition on extant buildings for preventing the construction from collapse with possible suggestions.

2. Research objects

Subjects of the study are 5 ancient brick shrines, N7, N8, N9, N10, N13, of Sambor Prei Kuk. Sambor Prei Kuk represents 7-10th century of Khmer ruins and is consisted of more than 200 brick shrines in Kampong Thom, Cambodia (at long.105.04E. by lat.12.87 N. Figure 1 and 2). The majority of building is made of burned bricks along with sand stone for the entrance and minor amount of wood. The brick structure is consisted by contacted masonry structure with irregular sizes of bricks and it is hard to find a striking laying patterns. Inside of the building is of high roof, the overlapping technique, so it has a high roof compare with an internal space letting the buildings have big loads. Hence, thick walls were necessary to enhance the stability. Many of buildings have collapsed and became mound-shape because the burning temperature of brick is low and buildings have been weathered over 1000 years. This research has conducted an analysis of 5 remains with well-preserved structure.

3. Method of study

To understand the structural displacement of Khmer brick buildings, specific measurement on the grade of tilt deformation of the walls, position and progress direction of cracks on the research objects was crucial. The
position and progress direction of cracks on objects and recorded on plans. Each situation mark as follows. "▲" when crack progress is going to up, "▼" when crack progress is going to down, "∥" when the progress direction is not sensed (Figure 4). To measure tilt deformation on walls, "digital level machine" is used. The machine measures the grade of tilted angle, 50cm away from a point on the targeted wall (Figure.3). To know tilt deformation of the entire building, each external walls were measured at 5 positions, 5 times each. Internal sides of walls were measured at 3 position, 5times, 2m above from the ground level on less weathered surfaces.

The value has come out by averaging 3 middle dates, excluding extreme ends. To revise the value, the Digital Level Machine is regularly reversed 180 degrees and all tilt direction and angle are marked on each plans by arrows. Each 1 degree is marked as 1m scale. And arrow directions means tilt directions. When walls is not tilt, marked as "="(Figure 4).

4. Measurement result and analysis

(1) N7 : The entire building inclines to the north-west. The outer wall of NE is tilted 3.3degrees and inner of SW is tilted 4.2degrees. NW, N, NE walls are tilted towards outside. Each corner has cracks because of the tilted walls. There are complex types of cracks, towards up or down. (2) N8 : Even though the superficial cracks on the wall, the walls are stable. (3) N9 : The entire building inclines to the East with few cracks. The outer and inner side of the West wall is tilted to the East 2.4 degrees and 1.7 degrees each. The East side of outer and inner wall is tilted to the East 3.1 and 1.6 degrees each. (4) N10 : There were no cracks and wall deformation found. But, inner walls are inclined to inside. The West side of inner wall is tilted 3.9 degrees. (5) N13 : The entire wall is inverted, mainly found on the East and South wall. The South wall is tilted 4.7degrees, with cracks progressing on every four corners.

Structural deteriorations are categorized into 4 types by result. A. Each walls turn inwards (N10), B. Each walls turn outwards (N13), C. The whole building inclines to a particular direction (N7, N9), D. An irrespective deterioration has been caused on the tilted walls (N8).

Figure 1. Sambor Prei Kuk Monument. Figure 2. Prasat Sambor Group. Figure 3. Tilt Measurement.

Figure 4. Result of measurement (from left N7, N8, N9, N10, N13).
Type A and B is occurred by structural feature of Khmer brick buildings with a high roof, causing big loads. For an urgent restoration and fundamental preservation, type A requires inner supports and type B requires band typed supports. Type C is rather triggered from fundamental problems than the structure of the building since the whole deformation of walls are towards to the same direction. Hence a leaning support will be needed in case of urgent restoration. Type D can be occurred by external shock than ground movement. The study categorized wall N8 as type D. A bomb hole of 1m deep and 5m wide is seen in front of N8. That is the wall must to be damaged by external reasons rather than ground movement. Therefore, setting pillar style supports will be effective resolution for restoring type D in the building unless a sign of tilted walls is found.

5. Additional research

5.1. Topographic analysis

The necessity of an analysis on ground movement is a great part of figuring out of deformation of walls towards similar directions since the damage comes from the ground instability. On this study, we analyzed topography and predict movement of rain water. Research objects are N8 which has no foundational problem, and N9 with foundational problem. We measured relative height difference near the object by "Total Station (Leica Co.)", and make topographic map and predict movement of rain water by "Surfer", software for making topographic map.

Figure 5 is a measure result. A counter line has arbitrary number. A Unit is "m". N8 is located on the higher place than surrounding. Therefore rain water flow out without stagnant. So, we could guess foundation of N8 is not affected by rain water. On the other way, N9 is located on the lower place than surrounding. The height difference was made by a clearance work on middle of 1900's. Most of rain water gathers to near N9. Additional analysis to figure out the period and progress of landing formation is crucial to stabilize the ground that gathers water around the site N9.

Figure 5. Topographic map (left ; N8, right ; N9).

Figure 6. Wall thickness (N8 west).  
Figure 7. Inner structure.  
Figure 8. Loads mimic.
5.2. Precise measurement on wall shape

The result of the tilt deformation analysis found out that inner and outer wall of the central part of N8 West wall and the central part of N10 East wall were everted. So, structural problem on a wall rather than inclination of wall is speculated. The study took a precise measurement of the wall shape of N8 and N9 by "Total Station (Leica Co.)." The results have shown a few gradual everted curves on outer and inner West wall of N8. Both faces of wall are inclined to outside until 2.6m high, and it starts to incline inside after the height of 2.6m.

Figure 6 shows the thickness of the West wall of N8 according to the wall height. Horizontal is the height (mm), vertical is the thickness (mm). Even the line is rough because of weathered surface; the general wall shape can be shown. The presumable causes could be found from following reasons. A wall of Khmer brick building is consisted by 3 layers (Figure 7). At parts of wall surfaces, bricks are stuck together completely. But inside part is consist by loose stuck bricks and soil mortar. Therefore, there are physical differences on each wall. Load subsidence of inside of the walls made partial expansion (Figure 8). N9 also has a gradual curve not on the both side of the walls but with the same tendency of the rest of types.

6. Consideration

This study suggested a measure method for wall condition of the Khmer brick building. By the analysis, structural deterioration on Khmer brick building is classified into 4 types. 3 types are classified by the features of incline direction, and 1 type does not feature of incline. And we found Khmer brick structural feature effects to wall deformation by the precise measurement on the wall shape. The lack of enough research objects has brought a limit to the study. Even so, the measure methods of this study will be useful for deciding emergency measures and restoration methods for structural stabilization of Khmer brick buildings.

References

Design of Adobe Bricks from Local Raw Materials for Use in the Monuments of Earthen Architecture (Case of Adrar Hospital), Algeria

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Abstract

The earthen architecture has evolved through generations using local materials. The earthen material has proven its validity in time and its efficiency in the architectural solutions and design. Also this material has proven its capacity of protection against the influence of climatic and environmental factors. It meets the needs of the population and its social, cultural and economic development. Despite the advantages of the strengths and the many features that make earthen the first building material in desert areas, others disadvantages must be taken into account and improve to a more efficient use. The scientific study will improve the earthen material properties so that it becomes more resistant to humidity and erosion. Structural restoration of old buildings requires respect of their original architectures and knowledge of the characteristics of the materials used. To this end, our study aims to develop earthen compositions (Adobe), compatible with original materials building of the monument materials, with better performance, for a proper restoration. The results of physical and mechanical characteristics of the compositions prepared in laboratories showed performance characteristics and compatible with the materials of the Adrar hospital. These final results will allow us for proper restoration of the monument.

Keywords: Raw materials, Earthen architecture, Development earthen composition, Adrar hospital, Adobe, Characteristic, Restoration

1. Introduction

The Adrar hospital (Figure 1) was made in 1942, designed by French architect of Belgian origin, Michel Luycks. It was built in earthen brick (adobe) masonry earthen mortar (Figure 2). Its walls are composed of holders of roof vaults of different scopes and different heights. Adobe was made at earthen quarries outside the city of Adrar. The building has been abandoned since the early 1980s, which has increased its degradation. The building is rectangular in shape. It was located in a rectangular enclosure also (Figure 3). It consists of two main U-shaped bodies.

The buildings on either side of the main entrance to the compound, served as housing and guard houses. Abandonment of the building, land squatters, infiltration of rain water are the main causes of degradation, peeling plaster, stripping coating causing it clearly notes and tear of some parts of adobe bricks. The collapse of some walls and infiltration of rain water are visible. The lack of function of gargoyles and defective channels have an important role in the deterioration of the hospital. Some facades, including the main façade and the underpinnings of the walls, showing no alteration.

Restoration of Structures of old buildings, requires respect for their original architecture and knowledge of the characteristics of the materials used. To this end, our study aims to develop earthen compositions based on local raw materials compatible with the building materials of the monument, with better performance. To achieve our goal we determined the mineralogical and chemical compositions (XRD, Fluorescent X) raw materials, particle size by analytical method and physical characteristics. We then designed adobe compositions. The results of physical and mechanical characteristics of the compositions prepared in laboratories (CETIM, - 221 -

Proceedings of the International Conference on Conservation of Stone and Earthen Architectural Heritage 2014
FSI (ceramic), URMPE showed efficient and compatible with the characteristics of Adrar hospital building materials. These results allow adequate restoration of the monument.

2. Experimentation

The objective of our work is the development and characterization of an adobe earthen formulation compatible with the building materials of the Adrar hospital. So we try to provide some answers as to adequate restoration for old buildings of earthen architecture. To arrive at this goal, we first step characterizing the raw materials and additives used in the formulation of samples, and the second step, the design and characterization of adobes samples. The Figure 4 shows the organigram of the main steps performed in our work.

2.1. Characterization of the raw materials and additives used for the formulation of the samples

Raw materials and additives used in the formulation of adobe samples are of local origin. Table 1 shows the mineralogical compositions and Table 2 physical characteristics of raw materials and additives used in the formulation of the samples.

2.2. Formulation of adobes samples

Several adobe formulations were developed at the laboratory. The choice of compositions developed is based on a literature review, experiences lived by craftsmen and the results of the work in this area (Craterre, Corpus Rehabimed). The preparation of the samples is performed in prismatic molds dimension (4x4x16) cm, drying was carried out at room temperature (air), the temperature varies between days (22 to 38 ± 2°C).

Figure 1. Aerial view, the hospital (Photo: Y.Terki).

Figure 2. View of main entrance, the hospital (Photo: M.Hamiane).

Figure 3. Ground plan of the hospital (Made by BET Adrar).
The formulations are based on control compositions as reference (1V clay +3.5 to 5V sand + water). Additions of between 5 to 20%, of Tafza, straw, sebkha, air lime, and natural cement. The purpose of these additions is to improve the physical characteristics (porosity, shrinkage, humidity...) and mechanical properties (compressive and bending strength). Drying was carried out at ambient temperature in laboratory rooms, then the air (T = 22 ± 2 °C, with H = 50-64 %), then to (T = 36 ± 2 °C, with H = 65-68 %). This will allow approaching the real and natural in situ production and avoiding cracking. The straw fibers were cut homogeneously (length 3 cm) to better assess their effect on the characteristics of the material. The Figure 5 shows the steps of sample preparation.

Table 1. Mineralogical compositions of raw materials and additives used in the formulation of the sample.

<table>
<thead>
<tr>
<th>Raw Materials</th>
<th>Compositions</th>
<th>Red Clay</th>
<th>Yellow Clay</th>
<th>Green Clay</th>
<th>Sand Dune</th>
<th>Tafza</th>
<th>Sebkha</th>
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<tbody>
<tr>
<td>Clay</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>Additions</td>
<td></td>
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<tr>
<td>Sand dune</td>
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<td></td>
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</tr>
<tr>
<td>Straw, Tafza, Sebkha, Air Lime</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3. Characterization of adobes samples

The adobe samples were characterized (shrinkage, mass change, after 07, 14 and 28 days of drying). The mechanical characterization of adobes was made by type of standard NF P-196 at 14 and 28 days ages (after drying). The characterization results are given in Table 3.

3. Interpretation of results

3.1. Materials and additives used in the formulation samples

The main raw materials used in the formulation are red clay, yellow and green, which act as a binder and give the plastic character to the samples. The dune sand, black sand and yellow sand (figure 6 show the particle size of different sand), as a degreaser for regulating clays plasticity and participate in the maintenance of mechanical characteristics, the formation of the skeleton samples. Adding: Sabkha, Tafza, air lime, crushing brick and the natural cement aim to improve the physical characteristics (porosity, absorption, hardness) and the mechanical properties of the samples. All raw materials are natural, locally available within the region. Natural cement and crushing brick were imported from North and neighboring regions Adrar.

Table 2. Physical characteristics of raw materials and additions used for the formulation samples.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Ms (g/cm³)</th>
<th>Mv (g/cm³)</th>
<th>H (%)</th>
<th>PH</th>
<th>CaO_L (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green Clay</td>
<td>2.55</td>
<td>1.80</td>
<td>3.23</td>
<td>8.08</td>
<td>0</td>
</tr>
<tr>
<td>Yellow Clay</td>
<td>2.37</td>
<td>1.81</td>
<td>3.44</td>
<td>9.28</td>
<td>0</td>
</tr>
<tr>
<td>Red Clay</td>
<td>2.26</td>
<td>1.72</td>
<td>3.04</td>
<td>8.86</td>
<td>0</td>
</tr>
<tr>
<td>Tafza</td>
<td>2.13</td>
<td>1.78</td>
<td>0.41</td>
<td>9.34</td>
<td>0</td>
</tr>
<tr>
<td>Sebkha</td>
<td>2.19</td>
<td>1.18</td>
<td>0.62</td>
<td>9.35</td>
<td>4.48</td>
</tr>
<tr>
<td>Sand dune</td>
<td>2.60</td>
<td>1.52</td>
<td>0.88</td>
<td>/</td>
<td>0</td>
</tr>
<tr>
<td>Yellow Sand</td>
<td>2.02</td>
<td>1.53</td>
<td>0.40</td>
<td>/</td>
<td>0</td>
</tr>
<tr>
<td>Black Sand</td>
<td>2.19</td>
<td>1.60</td>
<td>0.30</td>
<td>/</td>
<td>0</td>
</tr>
<tr>
<td>Naturel Ciment</td>
<td>2.54</td>
<td>0.77</td>
<td>0.82</td>
<td>11.58</td>
<td>6.72</td>
</tr>
<tr>
<td>Air Lime</td>
<td>2.54</td>
<td>0.81</td>
<td>16.03</td>
<td>12.87</td>
<td>100</td>
</tr>
<tr>
<td>Crushed Brick</td>
<td>1.36</td>
<td>1.27</td>
<td>1.01</td>
<td>10.13</td>
<td>/</td>
</tr>
</tbody>
</table>

Legends: Mv=Apparent density, Ms=Specific density, CaO_L = Free Lime; H= Humidity

Figure 5. Shows the steps of sample preparation.
Mineralogical analysis shows that the red clay is a material suitable for the manufacture of adobes, especially in desert areas due to normal plasticity, which prevents excessive swelling and cracking. Particle size analysis has allowed us to choose the nature and percentage of sand to add to the composition of adobe.

### 3.2. Physical and mechanical characteristics of adobes

#### 3.2.1. Witnesses compositions

Three witnesses compositions were selected based on literature references and know-how of adrar craftsmen (1V clay + 3.5 to 5V sand + water). The composition (1V clay + 5V sand + water), gives the best physical characteristics (Mv: 1.77 g/cm³ and Ms: 2.07 g/cm³, with compressive strength of 1.30 MPa with a 0.40% shrinkage and a decrease in total porosity 14.49%), this led us to choose this composition as a reference in our study for the different additions.

<table>
<thead>
<tr>
<th>N°</th>
<th>Samples</th>
<th>Ms (g/cm³)</th>
<th>Mv (g/cm³)</th>
<th>H (%)</th>
<th>Shrinkage (%)</th>
<th>Porosity (%)</th>
<th>R comp (MPa)</th>
<th>R flex (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>CTE 1</td>
<td>2.24</td>
<td>1.86</td>
<td>1.47</td>
<td>1.42</td>
<td>20.43</td>
<td>0.85</td>
<td>0.59</td>
</tr>
<tr>
<td>02</td>
<td>CTE 2</td>
<td>2.22</td>
<td>1.89</td>
<td>1.42</td>
<td>0.71</td>
<td>14.86</td>
<td>0.86</td>
<td>0.52</td>
</tr>
<tr>
<td>03</td>
<td>CTE 3</td>
<td>2.07</td>
<td>1.77</td>
<td>1.19</td>
<td>0.40</td>
<td>14.49</td>
<td>1.30</td>
<td>0.56</td>
</tr>
<tr>
<td>04</td>
<td>CPA 1</td>
<td>2.67</td>
<td>1.83</td>
<td>1.40</td>
<td>1.42</td>
<td>31.46</td>
<td>1.25</td>
<td>0.51</td>
</tr>
<tr>
<td>05</td>
<td>CPA 2</td>
<td>2.14</td>
<td>1.81</td>
<td>1.15</td>
<td>1.42</td>
<td>15.54</td>
<td>1.32</td>
<td>0.51</td>
</tr>
<tr>
<td>06</td>
<td>CPA 3</td>
<td>1.98</td>
<td>1.68</td>
<td>1.78</td>
<td>1.42</td>
<td>15.15</td>
<td>1.76</td>
<td>0.54</td>
</tr>
<tr>
<td>07</td>
<td>CSB 1</td>
<td>2.26</td>
<td>1.87</td>
<td>1.36</td>
<td>1.26</td>
<td>17.25</td>
<td>1.49</td>
<td>0.54</td>
</tr>
<tr>
<td>08</td>
<td>CSB 2</td>
<td>2.84</td>
<td>1.86</td>
<td>1.32</td>
<td>3.55</td>
<td>34.50</td>
<td>1.11</td>
<td>0.57</td>
</tr>
<tr>
<td>09</td>
<td>CSB 3</td>
<td>2.40</td>
<td>1.88</td>
<td>1.82</td>
<td>4.97</td>
<td>21.66</td>
<td>1.46</td>
<td>0.56</td>
</tr>
<tr>
<td>10</td>
<td>CCH 1</td>
<td>2.36</td>
<td>1.81</td>
<td>1.13</td>
<td>1.97</td>
<td>23.30</td>
<td>1.04</td>
<td>0.55</td>
</tr>
<tr>
<td>11</td>
<td>CCH 2</td>
<td>2.42</td>
<td>1.78</td>
<td>0.74</td>
<td>2.13</td>
<td>26.44</td>
<td>0.15</td>
<td>0.60</td>
</tr>
<tr>
<td>12</td>
<td>CCH 3</td>
<td>2.47</td>
<td>1.77</td>
<td>0.93</td>
<td>2.84</td>
<td>28.34</td>
<td>0.94</td>
<td>0.58</td>
</tr>
<tr>
<td>13</td>
<td>CTF 1</td>
<td>2.14</td>
<td>1.82</td>
<td>1.16</td>
<td>1.42</td>
<td>14.95</td>
<td>0.63</td>
<td>0.65</td>
</tr>
<tr>
<td>14</td>
<td>CTF 2</td>
<td>2.84</td>
<td>1.84</td>
<td>1.41</td>
<td>1.26</td>
<td>35.21</td>
<td>0.65</td>
<td>0.58</td>
</tr>
<tr>
<td>15</td>
<td>CTF 3</td>
<td>2.15</td>
<td>1.89</td>
<td>1.51</td>
<td>4.26</td>
<td>12.09</td>
<td>0.95</td>
<td>0.56</td>
</tr>
<tr>
<td>16</td>
<td>CAJ 1</td>
<td>2.24</td>
<td>1.84</td>
<td>1.23</td>
<td>4.26</td>
<td>17.86</td>
<td>1.12</td>
<td>0.47</td>
</tr>
<tr>
<td>17</td>
<td>CAJ 2</td>
<td>2.40</td>
<td>1.83</td>
<td>1.39</td>
<td>4.68</td>
<td>23.75</td>
<td>1.24</td>
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</tr>
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<td>18</td>
<td>CAJ 3</td>
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<td>1.81</td>
<td>1.36</td>
<td>4.26</td>
<td>22.01</td>
<td>21.30</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Legends: Mv= Apparent density, Ms= Specific density, CaOL= Free Lime, H= Humidity, R comp = R comp compression, R flex = R flex bending.

![Particle size sand analysis](image)

**Figure 6.** Particle size analysis by sieving (sand).
3.2.2. Compositions with various additions

It is noted that increasing the percentage of straw decreases the density and the specific gravity and increases the compressive strength and flexural strength and stabilizes the shrinkage. The top three chosen compositions with additions:

- (1V clay + 4V sand + 5 % straw + water) with a compressive strength of 1.76 MPa, the flexural strength 0.54 MPa, and a low porosity of 1.42 % shrinkage.
- (1V clay + 5Vsand + 5% sebkha + water) with a compressive strength of 1.49 MPa, the flexural strength 0.54 MPa and a shrinkage of 1.26 %.
- (1V clay + 5V sand + 20 % sebkha + water) with a compressive strength of 1.46 MPa, the flexural strength 0.56 MPa and a shrinkage of 1.97 %.

4. Conclusion

- The development of adobes was based on witness’s samples which were made by earthen, sand and water, selected references and experienced Adrar craftsmen.
- The witness’s composition (1V clay + 5V sand + water) give the best physical and mechanical results compared to other compositions. She was chosen as a reference for other additions.
- The addition of 5% of straw and / or 5% Sebeka, can improve the physical and mechanical characteristics of adobe bricks. They increase the mechanical strength; the porosity decreases and stabilizes or reduces shrinkage.
- Local raw materials (red clay, green, yellow), sand dune and sebkha are suitable to be used for the development of adobe bricks.
- The addition of straw and sebkha material, or air lime can be added to these raw materials to improve their physical and mechanical properties.
- The red clay taken from quarries Adrar is moderately plastic, is suitable for the production of adobes bricks.

References

Study on Stone Deterioration Status of Seoul City Wall

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Abstract

The Seoul City Wall had been damaged by nature and human for so long, and restored by human. The wall is not only excellent Cultural Heritage but also a valuable material in history of human civilization. The Seoul city wall had been exposed to various deterioration factors for long time, due to this, stones composing walls are in deteriorated state. The purpose of the study is to investigate degree of stone deterioration of the Seoul City Wall, through analysis and survey of the result, to suggest a ground of establishing plan for preservation and management in the future. To this end, the study observed deteriorated status of stone composing walls, the major structural part with eyes, examined, and arranged the results.

Keywords: Seoul City Wall, Stone, Deterioration, Preservation, Management

1. Introduction

A City Wall (fortress) is generally constructed to defend the enemy’s attack from danger for the protection of people. It has the purposes of military use but also acting as an ideological purpose to show the dignity of the royal authority. It could be said that ‘Seoul City Wall’ was constructed to symbolize dignity of the royal authority rather than military purpose because there wasn’t any combats after the form of the foundation. The Seoul City Wall had been firstly constructed for about 40ri (approx. 16km nowadays) long in the fifth year of King Taejo(1396). In the third year of Sejong (1421) it was partially collapsed and the walls were repaired with mud. Since then, the wall was damaged by two major wars and was repaired by soldiers during the reign of King Sukjong. Afterwards there had been several small repairing works but it is thought that the Seoul City Wall was completed by the Kings Taejo, Sejong, and Sukjong.

The Seoul City Wall began to being damaged as the tram was introduced in efforts of modernization of the Korean empire. During Japanese colonization era, Japan tore down walls in a nationwide scale including the walls in Seoul (Gyeongsung at that time) under the name of urban arrangement. Through years the walls had been damaged by both nature and human, and were restored by human. The wall is not only an excellent cultural heritage but also a valuable material in history of human civilization. The Seoul City Wall had been exposed to various deterioration factors for a certain amount of time and due to this, the stones of the walls are in severe deteriorated state. The purpose of this study is to suggest the basis of the future establishment plan for the preservation and management through analyzing and studying the degree of stone deterioration of the Seoul City Wall. To ensure this end, this study will understand the present deteriorated condition of stones composing walls, which are the major structural part, by visual inspection and organizing the results.

Figure 1. Survey Section of Seoul City Wall.
2. Survey of deterioration status of the stones of Seoul City wall

2.1. Summary

As a city wall was an important defense facility, there were various attached facilities. Seoul City Wall has four main gates and four auxiliary gates with facilities like water gates. These facilities are the main structures of the composition of the city wall but this study is focusing on the investigation of the stone material of the wall. The stones were surveyed by dividing the total 18.6km length into 8 sections, and the characteristics of each section are described. [Figure 1] shows survey section of present condition. The blank section in the picture shows the demolished section where no traces of the walls were discovered.

2.2. Survey of each section

2.2.1. Heunginjimun-Hyehwamun section

Due to wood and grass growth, damage of stone was observed. Other deterioration such as efflorescence event and surface pollution were observed. Walls on Naksan Mountain peak is cut off by road, so it is used as a parking lot for community shuttle buses, which can be a potential harmful element. On the road towards Hyehwamun from peak, weathering and crack of stone are observed much. On the point close to Hyehwamun, these were observed_ deformation of whole walls, crack to give damage on structural safety, and joint breaking. On some parts, there were traces of repairing with concrete on the foundation stones and other parts were in a severe state that needs proper action (Figure 2).

![Figure 2. Deterioration status of Huenginjimun – Hyehwamun Section.](image)

2.2.2. Hyehwamun-Seongbukdong section

Walls below the mayor’s official residence are the most risky part due to damage by plant and the accompanying weathering. Some parts with thoughtless repairing are degrading walls. These walls need urgent measures. Most of the sections of remaining walls are exposed to roads and they were damaged due to improper repairing work. Stone of Gyeongshin high school was damaged by plantation and some of them were covered by reinforced concrete. Section that starts from Seongbuk-dong park had been damaged by plant but it wasn’t severe except weathering and cracking of some stones (Figure 3).

![Figure 3. Deterioration status of Hyewamun – Seongbukdong Section.](image)

2.2.3. Waryong Park-Changuimun section

This section is on the Bukaksan Mountain. As it is on the Mountain, the section from Waryong Park to Malbawi (stone) shows severe damage by plantation where management had not been done due to geological...
reasons. The steel structure on the way to Malbawi is a cause of pollution. There are some wire entanglements and painting graffiti but the structure has been comparatively well managed. Some part of old Yeojangbuwi is tilted and roof stone is mostly deformed or not matched correctly (Figure 4).

**Figure 4.** Deterioration status of Waryong Park – Changuimun Secion.

### 2.2.4. Changuimun-Sajik Tunnel section

Inwangsan section is on the Mountain area which shows damage by plant, but comparing with other mountain section, it is not so severe. For repairing work of this section, considerable concrete was used to fill the gaps between stones. Efflorescence of concrete can lead pollution of stone and accelerate weathering. On some part, deformation which is assumed as bowing and phenomenon with mixed joints are discovered (Figure 5).

**Figure 5.** Deterioration status of Changuimun – Sajik Tunnel Section

### 2.2.5. Sajik Tunnel-Sungnyemun section

Walls in Wolam Park were recently restored according to the excavation works and remains. The walls are showing cracks due to excessive load on the old stones. Other ruins and remains in the section from Donuimun site to Souimun site are scattered around and some of them buried inside concrete or suffering from surface deterioration. The area of from Souimun site to Sungnyemun shows artificial damage in the process of restoration work. Weathering and crack of stone have partially happened (Figure 6).

**Figure 6.** Deterioration status of Sajik Tunnel – Sungnyemun Section.

### 2.2.6. Sungnyemun-Namsomun site section

This section is in the Mountain area which shows damage by plantation. It has much damage from algae than the other sections. The place with the most severe biological colonization is a little downward from the National theatre from N Seoul tower. At two points, large roots of trees were penetrated through the walls and one point of the walls was reinforced with steel frame and wire mesh. After going down from the place with biological colonization, there is a place where stones are showing large gaps between each other and walls which seem to be totally deformed. It is assumed that it has structural problems which made the walls settle down to some state. Around the National theatre were a number of cracks due to excessive load according to restoration works on the upper part, but even though it is on the mountain area there were less damage by plantation (Figure 7).
2.2.7. Namsomun Site-Jangchungdan section

Walls of Jangchungdan section were well restored but the Yeojang (type of wall) on the starting part of Namsomun site seemed to have used excessive cement mortar and concrete. This section is characterized by weathering and cracks on stones. A structural crack penetrating the wall from top to bottom could be observed around the Jangchung gymnasium (Figure 8).

2.2.8. Jangchungdan-Heunginjimun section

Walls from Donghodaero to Gwanghuimun are mainly used as wall of row houses or housing. Apparently the condition seems to be comparatively good through visual inspection but it is difficult to assess exact condition of the structure because the lower part cannot be observed. Walls inside the Dongdaemun History & Culture Park were found during the construction of a new building which was excavated and restored. The lower part of the restored Igansumun (2-hole sluice gate) shows some cracks. There are also some trace of pollution due to water leakage and submersion. Old stone in walls extended from the Igansumun (2-hole sluice gate) shows some cracks (Figure 9).

3. Investigation of status survey results

As a result of examining the material condition of the Seoul City Wall, it is assumed to be broadly secure with structural safety. However, some places were falling-off with structural safety due to cracks. The areas are downward section of Seoul tower in Namsan section (around the National theatre), around Jangchung gymnasium and the low area from Naksan Mountain Park (toward Hyehwamun) etc. The main factor of damage was biological colonization. As walls are concentrated on the mountain areas near facilities like gardens, the surroundings are formed with roots of plantation growth, which accelerates the weathering of stone. This results with the rapid progression of loss of cross sectional strength.

Though walls below mayor’s official residence are not located in the mountain area nor situated near a garden, the walls show severe weathering which is a secondary damage caused by biological attack. The place
where there is a collapse risk by tree roots is in the downward area of N Seoul tower of the Namsan section (towards National theatre). In order to prevent damage from plantation, it would be necessary to make a buffer area without plants over 1.5m wide like the section from Sukjeongmun to Changuimun where damage by plant has not been observed in the mountain area. To relieve vertical compressive stress on old stones like some parts of Namsan and Jangchungdan section, the reduction of dead load is essential.

For walls of restored section, it should be judged if such restoration secures authenticity and excellent universal value of Seoul City Wall by deeply thinking filling material, artificial damage, effect on old walls ruins, overall harmony etc. By examining the part which presumably can has ruins though it had not been seen due to reinforcing stone wall, mortar, ground rise etc., it should be checked how much ruins can be additionally secured.

4. Conclusion

The Seoul City Wall, constructed during the Joseon dynasty, is one of the most important cultural heritages of Seoul. The most important material used for this city wall is stone but it has been exposed from the harmful environment over a long time resulting with loss of structural performance. Biological colonization has been the dominant factor of damage. The roots of plants are the main factor for accelerating weathering process of stone and this is observed all over the Seoul City Wall. Besides damage by plant, there are some cases that excessive load by restoration works caused cracks on stone. Bowing of the wall was also observed resulting with walls settling down. It is certain to preserve the remaining walls well as it is the beginning of keeping the authenticity of Seoul City Wall. Currently it is estimated that the wall is safe, but if the upcoming damage factors are neglected, it cannot be possible to pass on the wall to our next generation as it is now. Thus, it would be necessary to arrange measures for damage by plantation and control unreasonable restoration work followed by a strict evaluation and survey on the present state.

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Research on the Salt Weathering of Stone Monuments and Base Rocks

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Abstract

This research is related with the salt weathering of the base rocks. At stone monuments and base rocks, slide, freeze damage, biodeterioration, have occurred, and especially salt weathering is serious. It was difficult to compare objectively that the content of salts and the state of degradation, and to get to know what salts are contained in the base rocks without a crystal until now. Then, when the concentration of the sodium chloride on the surface of the base rocks was measured by a new method, the very high concentration was detected in the place which does not have the efflorescence. Although, weathering speed is said to be late and an influence is said to be little compared with a sulfate mineral, it is clear from the value that the degradation by sodium chloride has occurred and the weathering speed and influence must not be made light of, either. Therefore, the measurement of the chloride is considered to be an effective method for judging salt weathering objectively.

Keywords: Salt weathering, Concentration measurement

1. Introduction

At stone monuments and base rocks, slide, freeze damage, biodeterioration, etc. have occurred. In the cause of degradation, especially salt weathering is serious. We are investigating the remains caved on the base rocks for the purpose of medieval cave tombs and memorial called ‘Yagura’ (Figure1). Yagura is located in the area centering on Kamakura City, Kanagawa in Japan. In recent years, Yagura has also become brittle due to the degradation of the base rocks. And salt weathering has occurred also in the base rocks of this area. Then, as one of the indicators to determine objectively the occurrence focusing on salt weathering, we have tried to measure the salinity.

2. About salt weathering

Salt weathering is a phenomenon which the soluble salt contained in the base rocks moves with water and is crystallized on the surface. As a result, the base rocks are separated by the pressure when crystallizing or through the hydration of the crystal, or the surface of the base rocks is damaged by the crack or the efflorescence are deposited on the surface. Because a terrain of this area was raised from the seabed, salts are included in the rocks originally. Moreover, since it is close to the sea, the wind containing salts blows against the base rocks. Furthermore, the salts inside the base rocks are moved to the surface in the process which rain and groundwater pass along the base rocks. For such a reason, salts are supplied to the base rocks.

The efflorescence is sorted two kinds: the crystal exists through a year, and the crystal exists only during the limited period. The crystal exists through a year is calcium sulfate and calcium carbonate which consist primarily of calcium form the crystal of white crust on the surface of the base rocks (Figure2). They form the efflorescence of the shape of white crust on the base rocks surface. At first sight, it seems to cover and protect the base rocks surface. However, the inside could be a cave by growth of the crystal, or it may cause surface
exfoliation by the weight of the crystal. Compared with the photograph taken half a century ago, a state of the efflorescence is almost changeless and a growth speed is slow.

On the other hand, there is an efflorescence which deposits only between November and March when the temperature and humidity fall. It disappears after April when temperature and humidity go up. In recent years, the maximum temperature of summer in this area exceeds 35°C. The minimum temperature of winter in this area may be less than 0°C. During the day of the winter, it sometimes becomes more than 10°C, and could be about 20°C from the sunlight. The humidity of summer in Yagura exceeds 95%, and an average is also more than 70%. While the highest humidity of winter exceeds 90%, the minimum humidity falls to the level of 20%. This is a white or a transparent soft fiber type crystal, and is sodium sulfate and magnesium sulfate, etc. (Figure 3). The particles of the stone were mixed with the crystal, and the base rocks surface is worn little by little out.

3. Measurement of salinity concentration

Thus, the crystallized place is intelligible that salt weathering has occurred. But it was difficult to compare objectively that the content of salts and the state of degradation until now. Moreover, it is difficult to get to know what salts are contained in the base rocks without a crystal at the present stage. Then, the value as sodium chloride was measured by a new method among the salts on the surface of the base rocks. A process is 1 to 3 below.

1: The base rocks surface is wiped off with the gauze wet with water.
2: The detector tube is put into the water which rinsed the gauze used for wiping, and a value is read.
3: The amount of sodium chloride (ppm) is computed based on the value of the detector tube.

The relation between chlorine ion concentration and salt is as follows, and the computed chlorine iron concentration becomes equal to mg/m².

By this method, the wall with a comparatively good state which tool marks remains, the wall with a hard efflorescence and the wall with an elastic efflorescence were measured. In addition, the surface of the wall which deteriorated is curving greatly by abrasion and its structure maybe unstable. Then, the abrasion wall without the efflorescence was also measured. Measurement parts are Figures 4-7. Measurement results were summarized in Table 1.

\[
N = \frac{C \times L \times \frac{1}{\text{Cl}}} {\frac{\text{NaCl}}{\text{M}}} 
\]

- \( N \): Salinity (mg / m²)
- \( L \): Amount of water (ℓ)
- \( C \): Chlorine ion concentration (ppm)
- \( \text{NaCl} \): The molecular weight of sodium chloride
- \( \text{Cl} \): The molecular weight of chlorine
- \( M \): Measuring area (m²)
Table 1. The results of measurement.

<table>
<thead>
<tr>
<th>No.</th>
<th>Measurement part</th>
<th>Amount of sodium chloride (ppm)</th>
<th>Situation of crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>November</td>
<td>January</td>
</tr>
<tr>
<td>1</td>
<td>The upper part of a wall</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>The upper part of a wall</td>
<td>300</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>The lower part of a wall</td>
<td>1900</td>
<td>3100</td>
</tr>
<tr>
<td>4</td>
<td>The abrasion wall</td>
<td>46400</td>
<td>41200</td>
</tr>
</tbody>
</table>

However, because the amount of sodium chloride is calculated in this method other chlorides are not included in the value. Therefore, sodium chloride cannot be considered as only cause of the degradation. For example, much sodium sulfate may also be contained in the measurement part. The wall at a good state (No.1) and the wall with a hard efflorescence (No.2) showed low values. The place of the crystal which exists only in winter (No.3) compared with them showed higher value. The value of No. 4 without the efflorescence was very high. Such a state of a wall and tendency on the value are common at other areas.

The value of the table 1 is the 1st wiping. For example, measurement was repeated until the value in April of No. 4 would not change. The total sum was 31300 ppm. The surface of the wall abraded and showed very high value is the sandstone layer with sunny fine particles, and there are common features, like the angle is roundish (Figure 8). Furthermore, reaction velocity is so quick that the high value is detected in several months again.

4. Conclusion

It is as follows when this measuring method is summarized. There are some advantages.
- Although measurement of chloride has done commonly by ion chromatography, this method does not need an expensive large-sized machine like ion chromatography.
- Furthermore, a procedure is easier than ion chromatography, and less time consuming. In addition, the correlation coefficient of this measuring method and ion chromatography is 0.99.
- Since a result is known immediately at a measurement place, working efficiency improves.
- The stone monuments are not damaged fundamentally.
- It can be evaluated objectively by quantifying a state of degradation. But there are some challenges.
- Any chlorides other than the sodium chloride contained in a measurement part cannot be measured simultaneously.
- The place where the surface may possibly break cannot be measured.
Since paints of a wall with coloring may also be wiped off, they cannot be measured. This measuring method has not been established yet. However, the measurement of the chloride is considered to be an effective method for judging salt weathering objective. Since it is hard to crystallize in the usual outdoor environment, it is hard to find the salt weathering by sodium chloride. Although, weathering speed is said to be late and an influence is said to be little compared with a sulfate mineral, it is clear from the value that the degradation by sodium chloride has occurred and the weathering speed and influence must not be made light of, either. We would like to improve challenges and to strive for establishment of the measuring method which is useful for preservation of stone monuments.

References

A Study on the Application of Steel Stiffeners to the Structural Reinforcement of Stone Cultural Properties

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Abstract
When only epoxy resin is applied to the injection, the parent material is regenerated by just 70%. Accordingly, it requires that the metal stiffener should be structurally reinforced as regards the other 30%. The metal rod is under structural behavior after the brittle failure of stone material; structural behavior does not occur when the metal stiffener comprises less than 0.251%; when it accounts for over 0.5%, it achieves structural reinforcement but causes the secondary damage of parent material. In the case of stone material having a strength of 1500 ksi/cm², resultinglly, the metal stiffener should comprise 0.283% to 0.377% in order to achieve reversible fracture and interactions associated.

Keywords: Epoxy resin, Metal stiffener, Structurally reinforce, Brittle failure, Interactions associated

1. Introduction
Stone cultural heritages are repaired by the use of metal stiffeners. The problem is that such repairs have been based on experience without systematic guidelines and, as a result many problems have occurred. This is to suggest the structural reinforcement and behavioral characteristics of metal rods, as well as to establish guidelines on how to insert metal stiffeners without the secondary damage of parent material. In this regard, a test was conducted with specimens that met the foregoing conditions.

2. Research methods
Specimens were made by the use of epoxy resin adhesive (L-30), to which filler (zirconium silicate, woolastonite and talc) was added that they could have a higher bond strength and liquidity and be more resistant to chemical weathering and metamorphism. In the interest of structural reinforcement, round steel stiffeners (titanium rebar) were laid on the surfaces to be adhered to each other. The rebar is classified into plain type and ribbed type. The standardized specimens were left at room temperature for about 30 days and thus were completely hardened in terms of physics as well as chemistry, on which loading tests were conducted by the use of a universal testing machine (maximum, 500kN) in the Advanced Construction Material Testing Center at KEIMYUNG University (DAEGU, South Korea). In the load tests, one- and two-point jigs were used and were directly connected to UTM.

To analyze how the specimens would behave under deflection load, strain gauges were attached to the stone and rebar. It was programmed to control displacement automatically through a computer, but the maximum displacement of rebar had to be controlled manually, displacement was measured through LVDTs on both sides of the loading jig. The load was applied at a millimeter per minute under the monotonic loading program, and the loading conditions varied depending upon how big the specimen was and how many specimens would be used. A 3-point loading test was conducted as the loading points were putted in the center, and a 4-point test with loading points putted closer to the both side at equal intervals. To sum up, as shown in ‘Figure 1’, this research was carried out with specimen making, the 1st breaking test, the 2nd breaking test and data analysis, in order.
3. Specimen making

As shown in ‘Table 1’, a total of 20 specimens were used for this research. They measured 1500x800x300 or 1500x800x300 millimeters. In particular, a comparison was made between the values worked out from this research and ones from a previous research conducted with 5 specimens (B21 – B 25).

All of the standardized specimens were cleaved by wedges hammered into them, except ‘B5’ and ‘B6’, and then they were bonded again to reinforce them further. To make a comparison between them, two specimens ‘B7’ and ‘B8’ were re-bonded only with epoxy resin adhesive, but to other specimens, adhesive and rebar were applied together in accordance with standards. The strain gauge was put in the center of the cut surface, and the hole diameter was 4 millimeters wider than that of rebar in order that the rebar could be fixed better.

![Figure 1. Test methods.](image)

Table 1. The list of bending test specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Size(㎜) LxWxH</th>
<th>Reinforcement method</th>
<th>Loading program</th>
<th>Reinforcement center criteria</th>
<th>Length (㎜)</th>
<th>Diameter (㎜)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>800x400x300</td>
<td>Titanium</td>
<td>3 point</td>
<td>3/4(3)</td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>B2</td>
<td>Titanium</td>
<td>3 point</td>
<td>3/4(2)</td>
<td></td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>B3</td>
<td>Titanium</td>
<td>3 point</td>
<td>3/4(2)</td>
<td>center(1), 3/4(2)</td>
<td>300</td>
<td>12</td>
</tr>
<tr>
<td>B4</td>
<td>Titanium</td>
<td>3 point</td>
<td>3/4(2)</td>
<td>center(2), 3/4(2)</td>
<td>200</td>
<td>12</td>
</tr>
<tr>
<td>B5</td>
<td>Titanium</td>
<td>3 point</td>
<td>-</td>
<td></td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>B6</td>
<td>Titanium</td>
<td>4 point</td>
<td>-</td>
<td></td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>B7</td>
<td>Epoxy resins</td>
<td>3 point</td>
<td>-</td>
<td></td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>B8</td>
<td>Epoxy resins</td>
<td>4 point</td>
<td>-</td>
<td></td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>B9</td>
<td>Stainless</td>
<td>3 point</td>
<td>center(1), 3/4(2)</td>
<td></td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>B10</td>
<td>Stainless</td>
<td>3 point</td>
<td>center(1), 3/4(2)</td>
<td></td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>B11</td>
<td>Stainless</td>
<td>4 point</td>
<td>center(1), 3/4(2)</td>
<td></td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>B12</td>
<td>Titanium</td>
<td>3 point</td>
<td>center(1), 3/4(2)</td>
<td></td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>B13</td>
<td>Titanium</td>
<td>4 point</td>
<td>center(1), 3/4(2)</td>
<td></td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>B14</td>
<td>Titanium</td>
<td>3 point</td>
<td>center(2), 3/4(3)</td>
<td></td>
<td>200</td>
<td>12</td>
</tr>
<tr>
<td>B15</td>
<td>Titanium</td>
<td>3 point</td>
<td>center(2), 3/4(2)</td>
<td></td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>B16</td>
<td>Titanium</td>
<td>3 point</td>
<td>center(1), 3/4(2)</td>
<td></td>
<td>350</td>
<td>22</td>
</tr>
<tr>
<td>B17</td>
<td>Titanium</td>
<td>3 point</td>
<td>center(2), 3/4(3)</td>
<td></td>
<td>350</td>
<td>24</td>
</tr>
<tr>
<td>B18</td>
<td>Titanium</td>
<td>3 point</td>
<td>center(2), 3/4(2)</td>
<td></td>
<td>400</td>
<td>24</td>
</tr>
<tr>
<td>B19</td>
<td>Titanium</td>
<td>3 point</td>
<td>center(2), 3/4(3)</td>
<td></td>
<td>200</td>
<td>8</td>
</tr>
<tr>
<td>B20</td>
<td>Titanium</td>
<td>3 point</td>
<td>1/4(1), 3/4(2)</td>
<td></td>
<td>300</td>
<td>16</td>
</tr>
</tbody>
</table>
As shown in ‘Figure 2’, rebar was laid in the light of reversibility and dynamic relation with bending behavior. Rebar was laid that its area might be equivalent to 0.2% to 1.5% of the cross-section area, with the exception of ‘B5’ and ‘B6’ that were not reinforced and ‘B7’ and ‘B8’ bonded with epoxy resin adhesive. As regards the pieces of rebar that took up the same percentage in specimens, they were installed in different arrangements, thereby analyzing the dispersion effect.

4. Analytic values and results

4.1. Arrangement of stiffeners

Both ‘B1’ and ‘B3’ were reinforced by 300-mm-long titanium round bars with a diameter of 16mm, but those bars were laid in different arrangements. The two specimens were similar in breaking load (B1: 390.04kN, B3: 396.802kN), but such values were short of ‘B2’ measured at 541.156kN. Its breaking load was 14% higher than ‘B1’. Rebar, inserted into ‘B3’, were structurally stable against load and met the reversibility of materials. In the case of ‘B1’, rebar met structural stability to some degree but was found to be arranged inappropriately, which are more likely to cause secondary damage. Accordingly, it requires that rebar should be arranged according to forces that are applied to materials.

Figure 2. The locations where stiffeners were laid.
4.2. Percentages of rebar

As shown in ‘Table 2’, rebar was laid that its area might be equivalent to 0.2% to 1.5% of the cross-section area, wherewith breaking tests were conducted to analyze the behavioral characteristics of stone materials. Stone materials were broken when the breaking load was between 319.87kN and 390.04kN. Specifically, brittle

![Diagram of loading behavior and stone damage relevant to the location of rebar.](image)

**Figure 3.** A diagram of loading behavior and stone damage relevant to the location of rebar.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Experimentation condition</th>
<th>Metal bar size</th>
<th>Results of the examination</th>
<th>Metal bar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size(㎜) LxWxH</td>
<td>Reinforcement center criteria</td>
<td>Length (㎜)</td>
<td>Diameter (㎜)</td>
</tr>
<tr>
<td>B3</td>
<td>800x400x300</td>
<td>center(1), 3/4(2)</td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>B4</td>
<td></td>
<td>center(2), 3/4(2)</td>
<td>200</td>
<td>12</td>
</tr>
<tr>
<td>B16</td>
<td></td>
<td>center(1), 3/4(2)</td>
<td>350</td>
<td>22</td>
</tr>
<tr>
<td>B18</td>
<td></td>
<td>center(2), 3/4(2)</td>
<td>400</td>
<td>24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Experimentation condition</th>
<th>Metal bar size</th>
<th>Results of the examination</th>
<th>Metal bar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size(㎜) LxWxH</td>
<td>Reinforcement center criteria</td>
<td>Length (㎜)</td>
<td>Diameter (㎜)</td>
</tr>
<tr>
<td>B3</td>
<td>800 x 400 x 300</td>
<td>center(1), 3/4(2)</td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>B14</td>
<td></td>
<td>center(2), 3/4(3)</td>
<td>200</td>
<td>12</td>
</tr>
<tr>
<td>B15</td>
<td></td>
<td>center(2), 3/4(2)</td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>B16</td>
<td></td>
<td>center(1), 3/4(2)</td>
<td>350</td>
<td>22</td>
</tr>
<tr>
<td>B17</td>
<td></td>
<td>center(2), 3/4(3)</td>
<td>350</td>
<td>22</td>
</tr>
<tr>
<td>B18</td>
<td></td>
<td>center(2), 3/4(2)</td>
<td>400</td>
<td>24</td>
</tr>
</tbody>
</table>
fracture occurred at about 380kN, except in the case of ‘B18.’ Also, the breaking load was found to be higher in rebar. In ‘B3’, ‘B16’ and ‘B18’, the values were 39%, 50% and 101.4%, respectively, higher in rebar than in stone. But in ‘B14’, it was 29% lower in rebar than in stone. The damage rate tended to be higher in specimens of which rebar comprised a higher percentage. Thus, the area of rebar should be adjusted to the material property of stone, at the same time, reversibility and secondary damage should be taken into consideration prior to reinforcement. Considering rupture stress and the theoretical burden of rebar, it is advisable that rebar makes up 0.28% to 0.5%. In order to do so, it needs to calculate compressive strength and cross-section area with respect to the object. Rebar must be installed and arranged based on the calculation.
4.3. Dispersion effect of rebar

The pieces of rebar were installed that they might have the same area but have different numbers, which was to analyze dispersion effect (Table 3). Diameter did not seem to have a significant influence on dispersion effect, but large-diameter rebar tended to be slightly superior; to be specific, ‘B3’ was 12.3% higher than ‘B14’, and ‘B16’ and ‘B18’ were 0.28% and 0.02% higher than ‘B15’ and ‘B17’ respectively (Figure 4). In the case of big materials, at any rate, it may be safer to distribute rebar evenly on the cross section rather than to concentrate it on a specific region.

If rebar is installed that it might be alongside of each other, in conclusion, the cross-section area of rebar will have some influence but its diameter will not do so. Another point is that rebar needs to be increased in the number of pieces and to be distributed more widely with consideration for effective stress and structural safety.

5. Conclusion

1. The pieces of rebar should be located as close as possible to each other in accordance with the quartering method in order to improve behavioral effects relevant to the maximum load and displacement. In addition, rebar should be installed that it can be perpendicular to compressive force.

2. Rebar can function as a tension member when it is laid below the central region of the cross section. If it is installed at the central region without the reinforcement of the tension side, a crack or shear failure may occur in the stone material, or secondary damage may occur from the yield strength of rebar.

3. The number of pieces of rebar does not affect load or displacement when those pieces have the same cross-section area. Thus, rebar should have a large diameter when the specimen has a small cross-section area, but when the specimen has a large cross-section area, the pieces of small-diameter rebar should be distributed widely in order that it can behave stably.

4. When rebar comprises 0.251% or lower, it leads to reversible breakage but cannot have structural function. On the other hand, the percentage of over 0.377% enables structural function but causes the shear failure of materials. Accordingly, it is best to adjust the percentage between 0.283% and 0.377% in order to make through with reversibility without the damage of materials and with dynamic reinforcement as structural frame at once.

5. The length of rebar does not affect the maximum load and displacement if it meets the effective length for structural reinforcement. Thus, the effective length should be designed as to the diameter of rebar. The following formula shows how to calculate it.
Effects of Shelter on Conservation of the Rock-carved Buddha: Rock-carved Buddha Triad in Seosan, Republic of Korea

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Abstract

The rock-carved Buddha Triad (National Treasure No. 84) in Seosan, Republic of Korea is a representative cultural heritage monument of Baekje Dynasty. A shelter was established in 1965 to prevent the weathering of the Buddha. However, the shelter was dismantled in 2007 because of diverse opinions that the shelter's internal environment causes deterioration of the Buddha and it doesn't promote proper viewing environment. Subsequently, conservation treatments such as cleaning, consolidating and surrounding maintenance were conducted in 2008. This study continuously monitored conservation state and environmental change of the Buddha after the dismantlement of the shelter and conservation treatments of the Buddha, and the results were compared before the dismantlement of the shelter. In addition, we studied the positive or negative effects of the shelter on the conservation of the Buddha. The results will be utilized as base data to establish conservation schemes of the rock-carved Buddha.

Keywords: Rock-carved Buddha, Stone cultural heritage, Shelter, Conservational environment

1. Introduction

The stone cultural heritage monument has been exposed mostly to the natural environment and has deteriorated due to the surroundings. Accordingly, it is necessary for conservational schemes to maintain its original form. The shelter is a representative method which protects stone cultural heritages from direct environmental changes (Shin et al., 2010) Therefore, the shelter was established when their conservation is urgent by serious weathering and damage. However, it is necessary to consider the problem and effectiveness of shelters because some matters, such as ventilation hindrance, dust deposition, dew condensation occurrence, and viewing interruption according to architectural form of the shelter have been raised.

Seonsan Rock-carved Buddha Triad is one representative cultural heritage which has a secondary problem about the shelter. Public opinion was formed that the internal environment of the shelter induces deterioration of the Buddha, and the shelter was dismantled to improve conservational environment. At this time, with the lapse of six years after dismantling the shelter, a detailed inspection before and after dismantling the shelter is essential for long-term maintenance and conservation of the Buddha. This study continuously monitored conservation state and environmental change of the Buddha after the dismantlement of the shelter and conservation treatment. The results were compared before the dismantlement of the shelter.

2. Current state

Seosan Rock-carved Buddha Triad has a sophisticated sculpture style and unusual position. The Buddha was found in 1959 and designated as National Treasure No. 84 in 1962 (Figure 1A). The shelter, having enclosed timber structure, was established in 1965 to protect the Buddha from natural environment and was maintained its form despite undergoing repair for a few times (Figure 1B).

However, the shelter continuously caused water leak and showed limited protection through the appearance of surface deterioration, such as dew condensation, dust deposition and efflorescence of the Buddha. In addition, the shelter has inconvenient spectating environment due to narrow space and poor light. Therefore, various
studies like the analysis of structural stability, deterioration evaluation and conservational environment were conducted to precisely identify the conservational state of the Buddha (Lee et al., 2006; 2010).

Subsequently, the shelter was partially dismantled in 2006 to improve conservational and spectating environments, and it was completely removed in 2007 (Figure 1C, 1D). In addition, conservation treatments and surrounding environment maintenance were carried out in 2008. Conservational treatments such as cleaning of surface contaminant (efflorescence, mortar, tar, etc.), filling and joining of the main crack and surface consolidation were performed (City hall of Seosan and C&T Inc., 2008). Currently, the Buddha has been exposed to outdoor environment regardless of any protective facility for six years now.


3. Condition before dismantlement of the shelter

The problem of water leak continuously occurs to the Buddha after the establishment of the shelter. Accordingly, various repair materials such as cement mortar, urethane and resins were used to prevent the water leak among bedrocks. However, the repair materials didn't solve the problem, but it added to damage due to secondary contaminants (Table 1). That is, the water penetration toward the internal of the shelter formed secondary contaminants such as soil deposition and efflorescence on the rock surface, and the rock surface was altered and weakened.

Table 1. Deterioration rate by weathering form of the Seosan Rock-carved Buddha Triad. CrD; Crumbly disintegration, Rf; Relief, Ex; Exfoliation, Bo; Break out, YbD; Yellowish brown discoloration, RbD; Reddish brown discoloration, Ef; Efflorescence, DrD; Dark gray discoloration, GrD; Green discoloration.

<table>
<thead>
<tr>
<th>Weathering form group</th>
<th>Weathering form</th>
<th>Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical weathering</td>
<td>Jo(No.)</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>CrD</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Rf</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>Ex</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Bo</td>
<td>2.8</td>
</tr>
<tr>
<td>Discoloration</td>
<td>YbD</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>RbD</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>Ef</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>DrD</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>GrD</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>42.7</td>
</tr>
</tbody>
</table>

Proceedings of the International Conference on Conservation of Stone and Earthen Architectural Heritage 2014
Analyzing the microclimate environment, the surrounding of the Buddha showed high relative distributions due to concentrated vegetation and mountain streams. The level of humidity inside and outside the shelter, where the Buddha Triad is located, has an average of 70% throughout the year, and the highest humidity level reached more than 95% in high frequency. The shelter in this environment has promoted long-term retention of water because it has a closed space structure.

In addition, inside the shelter is a more stable environment than the outdoor one. However, it maintained high relative humidity (99.9%) for a long time in the summer period and below zero temperature in the winter period. This means that the shelter doesn’t have excellent buffer function in response to change of the outdoor environment.

4. Condition after dismantlement of the shelter

The Buddha was mitigated with dew condensation more than before without the air current and sunshine because the shelter was partially dismantled and its three walls were opened. Subsequently, the shelter was dismantled completely. However the deterioration of the Buddha was prognosticated because the Buddha was exposed to the outdoor environment without any protective facility. The Buddha disclosed color and texture of the original rock due to the conservation treatment after the dismantlement of the shelter.

However, the Buddha showed efflorescence continuously after the treatment along the crack zones. Particularly, the biological colonization which is invisible before dismantlement of the shelter was expanded (Figure 2). Therefore, the continuous condition monitoring and the significance of prompt conservation action have emerged to protect the Buddha triad from unpredictable natural environment (Chun et al., 2013).

Figure 2. Conservation state of the Buddha after the dismantlement of the shelter and conservation treatment.

5. Discussion and conclusion

The shelter of the Seosan Rock-carved Buddha triad didn’t block the water penetration completely. The repair material used to prevent the water leak caused efflorescence on the surface of the Buddha. The material responding with water and soil along with the rainfall altered the surface. In addition, the shelter has promoted weathering because of hindrance and maintenance from water evaporation to the close space structure. Therefore, the shelter of the Buddha was dismantled by these problems. However, conservation problems such as efflorescence recurrence and biological colonization have been raised after an exposure to atmospheric environment without any facility protection.

The shelter is the best form to preserve stone cultural heritages from environmental change without direct manipulation. However, it is difficult to completely protect the stone cultural heritage monument even if its
shelter is excellent. Most shelters have problems particularly because they were built uniformly rather than designed individually to consider the state of each cultural heritage. Therefore, multiple studies are needed in order to provide a complete shelter design for stone cultural heritages. Furthermore, it is necessary to reflect a constructional design for shelter by specifically identifying the problems of each shelter.

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City Hall of Seosan and C&T Inc, 2008, Conservation Treatment of Seosan Rock-carved Triad Buddha, Korea, p.196. (in Korean)


A Comparative Study on the Analysis of Surficial Materials of Stone Cultural Heritage in Korea: with the Result of Analysis of 4 Stone Cultural Heritage as the Center

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Abstract

Stone cultural heritage has been diversely damaged or deformed by circumstances around each site, past repairs, and any other artificial touches. It makes stone cultural heritage have pollutant and the stuck secondary on the surface, but on the contrary there still remains original nature of them in the early or second stage of production. Through this study, it was performed to analyze surficial materials of stone cultural heritage, and to consider the result of testing chemical ingredients and phenomenon comparatively.

Keywords: Nondestructive analysis, Surficial materials, Whitening, Blackening, Dead lichen

1. Introduction

It was performed to analyze surficial materials of stone, which compose the followings; Rock-carved Buddha of Soraesan Mountain in Siheung (Treasure 1324), Seated Stone Buddha of Cheongnyongs Temple in Yecheon (Treasure 424), Seated Stone Vairocana Buddha of Cheongnyongs Temple in Yecheon (Treasure 425), and Icheondong Stone Buddha in Andong (Treasure 115).

In the process of investigating surficial materials of stone cultural heritage, it was conducted to test elements over an atomic number 15 with P-XRF (Portable X-ray Fluorescence Analyser α6000, Innov-X System), nondestructive analysis, for each 45 seconds in soil and leap mode. It was investigated for the parts turned white, black, reddish brown in the case of Rock-carved Buddha of Soraesan Mountain in Siheung, Seated Stone Buddha of Cheongnyongs Temple in Yecheon, and Seated Stone Vairocana Buddha of Cheongnyongs Temple in Yecheon, and investigated for the parts turned black and painted in red color in the case of Icheondong Stone Buddha in Andong.

2. Current and analysis object range

The weathering and the damage of the Rock-carved Standing Bodhisattva of Soraesan Mountain in Siheung, which has been exposed to the outdoor environment for a long time, have accelerated due to multiple influences of physical, chemical, artificial, and structural factors. The damages observed in the Rock-carved Standing Bodhisattva of Soraesan Mountain in Siheung included the physical damage such as rock cracking, breakage and loss, clefs, desquamation, and expoliation, and the darkening caused by the elution of Mn and Fe of the rock itself and the deposit of contaminants, and the darkening caused by the withering of lichen and moss, the whitening caused by the elution of Ca of upper ditch mortar, surface contamination such as the elution of iron oxide, and the biological damage caused by lichen and moss and herbaceous and woody plants that grow naturally in the clefs of rock. Particularly, the darkening phenomenon and cracking of rock surface are distributed over a wide area and are observed as the most serious damaging factor.

For the analysis of the ingredients of contaminants on the surface of the Rock-carved Standing Bodhisattva of Soraesan Mountain in Siheung, the analysis points were classified by contamination aspects into the fresh part (F), the whitening (W), the elution of iron oxide (R), the whitening on the upper ditch wall (W), the mortar (M), and the upper ditch presumed black paint (P), and a total of 15 points were analyzed (Figure 1). In the Seated Stone Buddha and the Seated Stone Vairocana Buddha of Cheongnyongs Temple in Yecheon, mechanical damage such as desquamation, expoliation, and decomposition of the standing statue is under way, and particularly, the surface contamination of darkening and reddish brown discoloration appears prominently.
Figure 1. Rock-carved Buddha of Soraesan Mountain in Siheoung (A; The front view, B; Whitening, C; lichen, D; Blackening, E; Mortar of upper drain, F, G; Reddish brown discoloration by chemical reaction).

Figure 2. Seated Stones Buddha of Cheongnyongsa Temple in Yecheon. (A; right Side-Seated Stone Buddha, left side-Seated Stone Vairocana Buddha, B; Whitening, C; Blackening, D; Reddish brown discoloration ).
For the analysis of the presumed pigment substance and the ingredients of contaminants on the surface of the Seated Stone Buddha and the Seated Stone Vairocana Buddha of Cheongnyongsam Temple in Yecheon, the analysis points were classified roughly into the Seated Stone Buddha (A) and the Seated Stone Vairocana Buddha (B), and, as classification detail, were classified into the white (w), the black (b), the red (r), and the fresh part (f), and the analysis was conducted on 9 points in the Seated Stone Buddha and 7 points in the Seated Stone Vairocana Buddha (Figure 2).

In order to compare the results of this analysis, the washing test part (s), the pedestal standing statue breakdown part (br), the tower of the stone pagoda (SP-1) in the front of the building in which this statue of the Buddha is located, and the iron decoration on top of the pagoda (SP-2) were measured. Also in the Rock-carved Standing Buddha of Icheondong in Andong, mechanical weathering such as desquamation, exfoliation, and cracking is occurring considerably, and the preservation treatment was under way in the condition in which the darkening, reddish brown discoloration, and surface contamination by lichen were accelerating (Figure 3).

For the analysis of the ingredients of the presumed substance of red pigment on the surface of the Rock-carved Standing Buddha of Icheondong in Andong, the analysis points were classified into the eye (re-(eye), 3 points), the lips (re-(mouth), 5 points), the neck (re-(neck), 4 points), and the fresh rock (fr- 4 points), and the analysis was conducted on a total of 16 points. Taking account of the fact that even the ingredients of the rock layer are analyzed as X-rays penetrate the thin contaminated layer in the analysis process of each object, the fresh surface of the configuration rock was measured as the comparison target and after passing through the filtering process, it was compared with the ingredients of the surface contaminants.

3. Result

In the case of Soraesan Mountain in Siheung, the parts turned white were caused by Ca formed by the mortar of upper drain, the parts turned black by dead lichen and paint ingredients of upper drain, and the parts turned reddish brown by Fe formed by eluted minerals inside stone through some chemical reaction (Table 1, Figure 4).
In the case of Seated Stone Buddha of Cheongnyongsa Temple and Seated Stone Vairocana Buddha of Cheongnyongsa Temple in Yecheon, the parts turned white were caused by Ca formed by limewash, and the parts turned black by discoloration by dead lichen. It can be verified by the enlarged photos through a microscope. Just like the above results of investigation, the parts turned reddish brown were caused by Fe formed by eluted minerals inside stone through some chemical reaction (Table 2–3, Figure 5–6).

Table 1. P-XRF Analysis data for Rock-carved Buddha of Soraesan Mountain in Siheoung.

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LOD: limit of detection.

Figure 4. P-XRF Analysis graph for Rock-carved Buddha of Soraesan Mountain in Siheoung.
In the case of Icheondong Stone Buddha in Andong, the parts turned black were similarly caused by discoloration by dead lichen. The parts turned red, estimated in the result of discoloration by pigment, have plenty of S, over 11% on average, and these ingredients of S are not extracted from traditional pigment except being extracted with Hg from cinnabar. Therefore, these ingredients of S, extracted through this investigation, are judged to be organic compounds from modern pigment (Table 4, Figure 7).

Table 2. P-XRF Analysis data for Seated Stones Buddha of Cheongnyongsa Temple in Yecheon.

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LOD: limit of detection.
4. Discussion and Conclusion

The investigation for surficial materials of the above stone cultural heritage has the common result that the parts turned black are discolored by dead lichen, and has the case-by-case result that the parts turned white are deformed by circumstances around each site, and has the result that the parts turned reddish brown are eluted in the surface of Fe minerals inside stone through the analysis comparison with parts of fresh stone. Especially, the parts turned red in Icheon-dong Stone Buddha in Andong, are judged to be not organic compounds from traditional pigment because ingredients of S, organic compounds from modern pigment, are extracted as main ingredients.

Table 3. P-XRF Analysis data for Seated Stones Vairocana Buddha of Cheongnyongs Temple in Yecheon.

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LOD: limit of detection

Figure 6. P-XRF Analysis graph for Seated Stones Vairocana Buddha of Cheongnyongs Temple in Yecheon.
Base on the data of surficial materials of stone cultural heritage accumulated thorough this kind of investigation, we are going to perform more in-depth studies. Moreover, we hope that the result of our investigations can be shared and utilized with any other similar investigation and contribute to the field of conservation science.

### Table 4. P-XRF Analysis data for Icheondong Stone Buddha in Andong.

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LOD: limit of detection

**Figure 7.** P-XRF Analysis graph for Icheondong Stone Buddha in Andong.
References


Monitoring Assessment Techniques after Conservation Treatment of Stone Cultural Heritage

Sung Mi Park, Yu Gun Chun, Mi Hye Lee, Myeong Seong Lee*
Conservation Science Division, National Research Institute of Cultural Heritage, Daejeon, Korea
E-mail: mslee75@korea.kr

Abstract

This study is assessment to the applicability by developing the technique to objectively and effectively monitor the surface condition and physical property change of stone cultural heritage. Photographing and weathering map use of grid was useful for identifying the damage location and condition. Digital portable microscope examination can identify the weathering conditions of configuration rocks of stone cultural heritage. The tape test was suitable for judging the difference in granular decomposition degree. Ultrasonic velocity was very useful for monitoring the changes in physical properties before and after conservative treatment. Accordingly these methods can be utilized as monitoring techniques for a long term and systematic conservative management of stone cultural properties.

Keywords: Stone cultural heritage, Surface condition, Physical property, Monitoring

1. Introduction

Currently the damage diagnosis of stone cultural heritage is to decide the time and direction of conservation treatment by diagnosing the current condition before the conservation treatment. It requires a lot of time and expertise. Accordingly for smooth preservation of stone cultural heritage a long term monitoring technology is required whose diagnosis is easy not only for professionals but also for practitioners of cultural heritage management. In this study, the possible long-term monitoring of cultural heritage administrators on how to conduct the research and application of cultural heritage conservation and stone were carried out.

2. Methods

In this study, for the stone cultural heritage with conservation treatment from 2002 to 2011 the monitoring method on changes in surface condition and physical properties was set and conducted. As monitoring method on changes in surface condition is photograph shooting, Digital portable microscope and weathering map for grid. The photographing is to take a long term observation on the same point. The grid setting method is to divide grids on a drawing of stone cultural properties in and to mark the damaged areas. It is the surface condition of stone cultural properties can be monitored. The digital portable microscope is observation of weathering of configuration rock and damaging the conservation treatment materials. As monitoring method on changes in physical properties is tape testing, ultrasonic exploration. The tape test was attach it to the surface of stone cultural heritage in cut plastic tape of 5cm × 2cm and to measure the weight of mineral particle detached. The ultrasonic exploration is to evaluate the internal properties of rock through ultrasonic velocity. The changes in physical properties before and after conservation treatment by measuring the location and condition photographed in the past in the same manner were identified.

3. Results

3.1. Monitoring the changes in surface condition

The photograph shooting is a simple, yet very useful method. Figure 1A shows the comparison with the
overall current view before and after the conservation treatment of Seoangni three-story pagoda located Gyeongju. The black and pale green creatures having intensively inhabited at the podium and capstone of stone pagoda before the treatment were removed when conserved and treated, but since the eight (8) years elapsed the black creatures have inhabited again. Like this if the overall appearance and a particular point are continuously in the same manner photographed and recorded at an interval of a predetermined period, the time and location, damage type of changes in surface condition can be monitored. In addition the determination of damage aspects of many stone cultural heritage can be monitored for a relatively little time.

Figure 1. Surface condition monitoring. (A) Comparison with pagoda status through photographing. (B) Comparison with damage map and weathering map using grids. (C) Identification of surface conditions using digital portable microscope.

Weathering map using grids was more simplified than existed damage map. Figure 1B shows the damage map and the weathering map using grids of three storied stone pagoda located at Seungansa site in Hamyang. The existing damage map enables us to relatively correctly identify the damage area and line, but it is more or less complicated, and for the calculation of damage rate the overall area and partial area have to be calculated using a particular program. On the other hand, for the weathering map using grids the determination of damage condition and location is easy and simple at a glance, which is more efficient in time and economy than preparation of existing damage map.

A digital portable microscopic examination can identify the weathering conditions of configuration rocks of stone cultural heritage, the type of contaminants and weathering aspects. In addition the gap of micro-cracks which is difficult to be visually observed and measured can be measured. As a result of using a portable microscope, due to the weathering of composition minerals it was identified that the mineral crystal is broken, whose combination force is weak and for the surface discoloration the black manganese oxide and yellow iron oxide were fixed. In addition, the micro-cracks generated at the stone pagoda were identified to have gaps of 1.115~2.771mm (Figure 1C). If a long term monitoring is periodically conducted on the same points using a portable microscope the damage type and degree of stone cultural properties can be precisely checked and the damage mechanism can be identified.

3.2. Monitoring the changes in surface physical properties

The tape test of physical property monitoring method is a monitoring technique to compare the weathering
degree of stone cultural properties by conveniently identifying the degree of granular decomposition generated on the rocks. The weight of particle exfoliated from the three-story stone pagoda at Seoak-dong, Gyeongju-si with preservative treatment conducted in 2004 is shown to have average 0.3mg, while the stone cultural properties with preservative treatment conducted from 2009 till 2011 to have average 0.1mg (Figure 2A). Whereas, the three-story stone pagoda at Seungan-sa site, Hamyang with preservative treatment conducted in 2007 is shown to have average 2.0mg. Through this for the granular decomposition the more recently the time having conducted the preservative treatment becomes the less exfoliation by particles of stone cultural properties, which is judged to show a difference depending on the configuration rocks and manufactured time, location and surrounding environment of stone cultural properties(Figure 2B). If the long term monitoring using tape test is conducted the standard to judge the risk of granular decomposition can be offered and the time to conserve and treat can be determined.

Figure 2. Change in the physical monitoring. (A) Result of the Tape test. (B) Difference in surrounding environment by location of stone cultural heritage. (C) Comparison with ultrasonic velocities before and after the conservation treatment.

The ultrasonic exploration is the method to quantitatively monitor the properties of configuration rocks of stone cultural heritage. As a result of comparison with the ultrasonic velocities before and after the conservation treatment, the average value of stone cultural heritage increased 47m/s ~ 240m/s than before conservation treatment treated from 2005 to 2009. On the other hand, the average value of stone cultural heritage with conservation treatment made in the year 2010 and 2011 decreased by 230m/s ~ 630m/s. For the ultrasonic velocities except Maayeoraesamjonsang (or the three seated Buddha's images) located at Yonghyeon-ri, Seosan it was shown that the range of ultrasonic velocity measurement values was wide and the average values were high after being commonly preserved (Figure 2C). Through this it was identified that the properties of stone cultural properties was lowering if three years have elapsed after the conservative treatment. If the long term monitoring is periodically conducted using the ultrasonic exploration it is possible to identify in which area the properties are improved and lowered. And it is effective for managing the cultural properties by identifying the re-treating time of conservation treatment.
4. Consideration and conclusion

The monitoring method of stone cultural heritage executed in this study is judged that not only the professionals but also the cultural properties related probationers can monitor through a simple training. Accordingly if the probationers primarily monitor the overall surface conditions and physical changes of stone cultural heritage and the professionals intensively monitor the stone cultural heritage with abnormal symptoms identified the effective and long term conservative management of many tone cultural properties will be made.

As a result of monitoring the surface condition and physical changes of stone cultural heritage, it was useful observe for monitoring weathering and combination condition, spacing of crack. The ultrasonic velocity was identified that the physical properties are gradually lowering after three years in conservation treatment. Therefore regular monitoring is performed every three years to check the status of stone cultural heritage and maintenance management system should be to determine reprocessing.

References


Analysis on Damaged Characteristics of Stone Objects in the Tajo’s Geonwolleung of Jonseon Royal Tombs, World Cultural Heritage

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Abstract

Tajo’s Geonwolleung is the tomb by the Joseon’s 1st king, Lee Seong-gye of the 42 Joseon Royal tombs. Currently the stone objects laid out at Geonwolleung are 168 burial mound stones and 26 stone objects, which have been exposed to the external environment for a long time and considerably weathered. Accordingly after the damaged condition on plants in the Geonwolleung is diagnosed and surveyed the measures for conservation and management of each stone objects were proposed. As a result, as the damage ratings are 0.0% for class 1, 13.9% class 2, 34.5% class 3, 51.5% class 4 it is actually urgent to conserve and manage the burial stones and stone objects at Geonwolleung. Therefore, in order to conserve and manage the stone objects for a long time it is necessary to generally wash the surface, some stone objects are judged to have the conservative measures such as consolidated treatment, adhesion and filling, etc.

Keywords: Royal Tombs of Joseon Dynasty, Geonwolleung, Stone objects

1. Introduction

Tajo’s Geonwolleung is the tomb by the Joseon’s 1st king, Lee Seong-gye of the 42 Joseon Royal tombs registered as 2009 world cultural heritage. Currently it is located at the area of Dongureung in Inchang-dong, Guri-si, Gyeonggi-do(Historic Site No.193), whose stone objects are classified into the burial mound stones and stone objects. The burial mound stones are laid out with the stones made of granite related to the retaining stone and guard rail stone surrounding the burial mound and various stone objects with animal objects, human objects, and other related stone statues laid out around the tombs (National Research Institute of Cultural Heritage, 2009). Currently the stone objects laid out at Geonwolleung 168 burial mound stones and 26 stone objects, which have been exposed to the external environment for a long time and considerably weathered. Accordingly in this study the understanding of the current situation on the burial mound stones and stone objects laid out at Tajo’s Geonwolleung and its diagnosis and survey of deterioration status were conducted, accordingly the conservation and management measures were proposed.

2. Methods

The burial mound stones and stone objects at Geonwolleung have been exposed to the external environment for a long time, of which the physical chemical and biological weathering has been considerably progressed. Accordingly for the damage diagnosis on the weathering and conservative condition of stone objects in the Geonwolleung the conservation and management diagnostic sheet was prepared and surveyed. The diagnostic sheet consists of the general status and configuration rock of stone objects, damage condition and conservative measures. The damage conditions among these are classified into the surface weathering, surface discoloration, biological effects, structural condition, which are designed to check the damage aspects, damage ranking appearing at each item. In addition the damage ratings were classified and evaluated into class 1 up to class 5 referring to existing weathering ratings studied (Lee and Lee, 2005; Jun et al., 2006; The Korean Society of
Conservation Science for Cultural Heritage, 2001~2005), the general damage ratings with ratings integrated by damage condition of each (classified into 4 groups) were calculated, and the basic conservative and management measures were proposed.

3. Current status

The stone objects of royal tomb are classified into the burial mound stones and stone objects. All of these stone objects consist of biotite granite. The burial mound stones are retaining stone (Byeongpungseok) and guard rail stone (Nanganseok) surrounding the burial mound, whose stone objects are animal object, human objects and other related stone statues laid out around the royal tomb and burial mound. The total number of burial mound stone in the Geonwolleung is 168. The burial mound stones are surround retaining stone (Byeongpungseok) and various connection members comprising such as foundation stones (Jidaeseok), corner stone (Useok), holding stone (Inseok), cap stone (Manseok), etc. In addition 12 stone pillars (Seokju) and small stone pillars (Dongjaseokju) and 24 guard rail stones (Nanganseok) are surrounded outside the retaining stone, 36 roof-tile shaped foundation stones (Wachamsangseok) were used on the ground surface between guard rail stones.

For the stone objects the 26 units of human objects (stone men) and animal objects (stone animals) are symmetrically right and left laid out at three stairs such as upper, middle, and lower stairs from the center of burial mound. At the upper stair the two pairs of stone tigers and stone sheep are alternately laid out on both the right and left sides of burial mound beginning with stone sheep, which are looking outward. At the middle stair there exist a pair of stone image of civil officials with the center of stone lantern and table for the spirit stone in the center of burial mound, while at the lower stair side by side with stone image of civil officials there exist a pair of stone image of military officials and two pairs of stone horses standing facing each other (Figure 1).

4. Result and discussion

As mentioned previously, damage types of stone objects in the Geonwolleung are classified surface weathering, surface discoloration, biological effects, structural condition, etc. First the surface weathering shows varied phenomena such as exfoliation, granular decomposition, break out, cracks, etc. Especially the burial mound stones such as retaining stone, guard rail stone, stone pillar predominantly show exfoliation and granular decomposition, while the stone objects such as stone lantern, stone tiger, table for the spirit stone and the stone image of civil officials and stone image of military officials are mainly observed to have the phenomena of break out of material and exfoliation. The surface discoloration of stone objects is identified to include yellow discoloration, black discoloration, soil, etc. In particular, the soil when the environment with burial mound is
considered is predominantly identified at the burial mound stones such as corner stone, plate stone and foundation stones.

The stone objects in the Geonwolleung are the most severely damaged by the biological effect. At both the burial mound stones and stone objects the bio-habitat is observed, among which the coating by lichens, mosses, herbaceous plants is the severest. For a typical example at the foundation stones and flat stone near the ground surface the coating by herbaceous plants was high, while the guard rail stone, retaining stone, cap stone far from the ground surface are mainly contaminated with lichens, mosses. In addition for the structural conditions the displacement of guard rail stone pillars and the slope of small pillar (Mangjuseok), small stone pillar (Dongjaseokju) and separation of cap stone, etc. are identified (Figure 2).

![Figure 2. Damage condition of stone objects in the Geonwolleung.](image)

**Table 1. Damage diagnosis result of stone objects in the Geonwolleung.**

<table>
<thead>
<tr>
<th>Rating</th>
<th>Surface weathering</th>
<th>Surface discoloration</th>
<th>Bio-effects</th>
<th>Structural condition</th>
<th>Synthesis damage condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>Ratio (%)</td>
<td>No.</td>
<td>Ratio (%)</td>
<td>No.</td>
</tr>
<tr>
<td>Class 1</td>
<td>0</td>
<td>0.0</td>
<td>122</td>
<td>62.9</td>
<td>1</td>
</tr>
<tr>
<td>Class 2</td>
<td>10</td>
<td>5.2</td>
<td>40</td>
<td>20.6</td>
<td>17</td>
</tr>
<tr>
<td>Class 3</td>
<td>123</td>
<td>63.4</td>
<td>27</td>
<td>13.9</td>
<td>37</td>
</tr>
<tr>
<td>Class 4</td>
<td>51</td>
<td>26.3</td>
<td>4</td>
<td>2.1</td>
<td>43</td>
</tr>
<tr>
<td>Class 5</td>
<td>10</td>
<td>5.2</td>
<td>1</td>
<td>0.5</td>
<td>96</td>
</tr>
<tr>
<td>Total</td>
<td>194</td>
<td>100.0</td>
<td>194</td>
<td>100.0</td>
<td>194</td>
</tr>
</tbody>
</table>
As a result of summarizing the damage conditions of each stone object, the surface weathering had the most of 123 (63.4%) of class 3, the surface discoloration and structural condition had the most of 122 (62.9%) and 174 (89.7%) of class 1, the damage by surface discoloration and structural condition was not significant. However the bio-effects had the most of 96 (49.5%) of class 5, for which the conservative treatment is actually required. Looking at the synthesis damage conditions of stone objects, 27 (13.9%) of synthesis class 2, 67 (34.5%) of synthesis class 3 and 100 (51.5%) of synthesis class 4 the higher damage rating becomes the share rate increases. Especially for the severe damage conditions like class 5 due to more than 50% of ratio the urgent conservative management are required (Table 1).

Thus, the burial mound material and stone objects with severe surface damage are judged to need the conservative treatment such as consolidated treatment and adhesion and filling with surface washing. However for the long term conservative management it shall be performed through a process of consultations and the public consensus, even after the conservative measures having been conducted the ongoing conservative measures is urgently required. In addition, various researches such as impacts by surrounding environment, causing damage identification, study on conservative treatment measures, etc. it shall be progressed, on a basis of which the effective conservative management is judged to be conducted. More research in the future can be utilized as a data base in the study on conservative conditions on stone objects of Joseon royal tombs and provided as basic data to establish the conservative management measures for stone objects.

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Detection of Hygroscopic Salts before the Apparition of Degradation Patterns: Experimental Approach on Limestones Using the Stimulated Infrared Thermography

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Abstract
Recent improvements of infrared thermography cameras allow detecting small defects and hygroscopic salts that are present under the surface of building heritage materials. Preliminary laboratory experiments have been conducted and they show that it is possible to detect salted area in a limestone. Thermophysical properties of materials in presence of salts have been studied. The effusivity (b) and thermal diffusivity (a) have been thus characterized according to ways: measurements under an extended flash excitation and measurements on the center of the excited area after stimulation. The results show that these parameters are very sensitive to the presence of salts. It is then possible to detect the crystallization process of hygroscopic salts at its first steps and to localize the crystal germs inside the stone.

Keywords: Hygroscopic salts, Stimulated infrared thermography, Detection, Emissivity, Diffusivity

1. Introduction
Conservation of cultural heritage needs to detect and to identify the first signs of future alteration. These threats can have a physical, a biological or a chemical origin. Hygroscopic salts are well-known to be one of the major causes of degradation of stones surfaces and wall paintings (e.g. Alonso et al, 2008, Benavente et al, 2007, Doehne, 2002, Gomez- Heras & Fort, 2007, Goudie, 1999, Schaffer, 1932 and Winkler & Singer, 1972). They are generally detected when degradation patterns such as blistering, powdering according to Anson- Cartwright et al (2008) appear. Therefore investigations currently aim to try to detect salts infiltrations using nondestructive methods such as the stimulated photothermal radiometry (SIRT) for few years (Bodnar et al, 2012; Nachshon et al, 2011).

The present work aims to show the SIRT’s potentialities in this domain and to highlight the thermal behavior of building materials in presence of salts. More, experimental results on the ability to detect salts in a stone, to measure the thermophysical properties of these materials that can be impacted by salt contamination and to study the crystallization process are presented here.

2. Materials and method
The experiments have been conducted using two Miliolids limestones from Lutetian period and a sample of brick in A protocol. “Pierre du Midi” which is a bioclastic detrital limestone from the Burdigalian period was used in B protocol.

2.1. Experimental detection of the manifestation and presence of salts
A. protocol
The first experimental protocol aims to determine if the detection of crystallization phases on different types
of samples is possible. Three samples are placed on a grid (two Miliolids limestones from the Paris Basin and a brick) in the ambient conditions (19 °C, 60% RH). The samples were previously immersed overnight in a saturated solution of Na$_2$SO$_4$ saturated (14%).

A thermal camera recorded continuously the thermal signal emitted from 3 samples during 5 hours in order to detect any temperature changes indicating a phase change (from the liquid phase to the solid phase or hydration phenomena inducing crystalline structure changes such as in presence of mirabilite and thenardite). The records occurred using a FLIR A20 bolometers thermographic camera operating in the 7.5-13 µm spectral range. The acquisition frequency was set at 1 frame every 5s, and the distance between the camera and the sample was 20 cm. The lens used is the objective of the standard A20 FLIR (Field of view/min focus distance 25° x 19° / 0.3 m, Spatial resolution (IFOV) 2.7 mrad and Thermal sensitivity @ 50/60Hz 0.12° C at 30° C).

B. Protocol

The second experimental protocol includes two experiments. It aimed to test the capacity of the stimulated infrared thermography (SIRT) to detect the presence of hygroscopic salts on the base of the characterization of two thermophysical parameters. The same camera as previously has been used.

2 sets of 5 stone samples have been then drilled in the stone. A single set has been plunged in a saline solution that contained 4% in mass of NaCl during 8 hours in ambient conditions (T = 20 ± 3°C). After their emersion, the samples were air dried during more than 48 hours. The other set was not treated and a PVC sample was used as a reference. All the samples have been painted in black using a high temperature spray paint in order to increase the detection contrast and improve the thermal homogeneity of the samples.

1st experiment: determination of the thermal effusivity $b$

Saline and unsalted samples have alternatively been deposed side by side and beside the PVC reference in front of the camera (Figure 1). They have been lighted by a daylight flashing light (Figure 2), the flash output is 1500 W. The thermal signal was recorded during 2 seconds. The distance between the camera and the sample is 20 cm. The lens used is the same than previously. The samples have thus a thermal response depending on their single thermal properties which depends on their crystal-chemical composition. The experimentation has been made five times paying attention to have identical conditions in terms of energy deposit on the samples surface. Their thermal response during the cooling has been more particularly observed and the profiles of the decrease in time of the average temperature that was calculated using the five experiments have been extracted from the recording using Thermacam Researcher software © from FLIR (Figure 3).

![Figure 1. View of the samples before (a) and during the thermal excitation (thermal image; b). The black square section sample is the PVC reference. The blue circles correspond to the location of the temperature readings.](image)

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1 The thermal effusivity $b$ of a material characterizes its ability to exchange thermal energy with the environment which is in direct contact. The material with the highest effusivity imposes its temperature to the material having a lower effusivity. This means that the equilibrium temperature (long time) will be closer to the temperature of the effusive body ... It depends on the thermal conductivity, the density and the thermal capacity of the material. It is expressed in $\text{JK}^{-1}\text{m}^{-2}\text{s}^{-1/2}$. 

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The sensitivity of the measure has been verified on a block of limestone (Figure 4) which has been impregnated in its centre by a NaCl solution at the same concentration as previously (15 ml of the solution have been deposed as successive droplets). The salted area is about 5 cm in diameter. The spatial variations of effusivity on the same samples were then observed in order to evaluate the effects of the samples heterogeneity in the parameter b variations. The same heating protocol as before has been applied and the evolution of the temperature has been observed along a lateral profile crossing the salted area (Figures 4 and 5).

2\textsuperscript{nd} experiment: determination of the thermal diffusivity $\alpha$

The thermal diffusivity ($\alpha$) was determined on the same set of 10 samples: a Dirac pulse was sent on each of the samples using the same flash and the evolution of the thermal response on the rear face was then measured using the same camera clocked at 100 Hz (Figure 6).

Figure 4. Stone impregnated with NaCl in its centre (a) and its thermal image that shows the lower temperature of the salted area (in the blue at the centre of the image; b). The blue circles on the thermal image correspond to the location of the temperature readings.

Figure 5. Comparison of the cooling profiles versus time from the references (in red) and the salty samples (in blue).

The thermal diffusivity ($\alpha$) (unit m$^2$/s) is a physical quantity which characterizes the ability of a continuous material to respond to a thermal stress from one point to another one on the same material. It depends on the material’s ability to conduct heat (thermal conductivity) and its ability to retain heat (produced mass density x heat capacity). This property is directly involved in the heat equation, so it is a fundamental quantity. Some materials will be rather heat conductor, and other will be heat accumulators. In case of stones like limestones, the $\alpha$ value can vary from $1 \times 10^{-7}$ to $1 \times 10^{-6}$ m$^2$/s depending on the nature of the materials, moisture etc.
2.2. Study of the crystallization manifestation

Several authors (e.g. Rodriguez-Navarro, C., & Doehne, E. 1999 and Selwitz, C., & Doehne, E. 2002) studied the crystallization processes implementing different types of salts but none of them worked on the thermal effects occurring because of a salt crystallization process. So, in order to show the ability of infrared thermography to detect the thermal event induced by the salt crystallization process and to identify the occurrence of salt crystals within the stone, three samples were observed since their emersion from the saturated solutions (Figure 7). The second objective is first to study the kinetics of appearance of these salts on samples subjected to the same immersion conditions and the same climate and secondly to highlight the relative impacts of saline infiltrations (Figure 7) on two Miliolids limestones (stone of Branscourt (BRA) and stone of Hermonville (HER)) and a sample of artificial stone brick (BRI).

2.3. Measurement of the thermophysical properties in presence of salts

The thermal effusivity (b) was obtained using a comparison method of the temperature response of the samples versus a calibrated reference (sample of PVC). Five samples of stones have been studied. All the samples and reference received the same excitation with the flash before and after the application of the salting protocol as defined previously. A 1D theoretical model developed on short times has been applied. As exposed in the literature (e.g. Carslaw and Jaeger, 1959), the evolution of temperature is a function of time that can be written as follows when a semi-infinite flat surface is exposed to a brief excitement over its entire surface:

![Experimental thermal diffusivity measurement](image.png)

**Figure 6.** Experimental thermal diffusivity measurement: temperature response of a sample back surface (in red) and adjustment to the theory (in black).
\[ T(0,t) \approx \frac{Q}{\sqrt{\lambda \rho c \sqrt{\pi t}}} = \frac{Q}{b \sqrt{\pi t}} \]  

(1)

With:

\( b \) Thermal effusivity (JK\(^{-1}\).m\(^2\).s\(^{1/2}\))

\( c \) Thermal capacity at constant pressure (J.m\(^{-3}\).K\(^{-1}\))

\( \lambda \) Thermal conductivity (W.m\(^{-1}\).K\(^{-1}\))

\( \rho \) Density (kg.m\(^{-3}\))

\( Q \) Energy deposition (J)

\( t \) Time (s)

This last expression (1) shows that the temporal evolution of the temperature in the first moments of the photothermal experiment is simply related to the thermal effusivity of the studied material (b). However, the problem arises from the knowledge of the energy deposited Q. The formula shows that Q must be known precisely to achieve a good estimation of the thermal effusivity. In our case study, this estimate is based on the comparison to a reference material taking into account that the both radiative properties of the reference and the studied sample are identical because they all are painted black and because the thermal effusivity was perfectly known. Under these conditions, we can express as follow:

\[
\begin{aligned}
T(0,t)_{\text{unknown}} &= \frac{Q}{b_{\text{unknown}} \sqrt{\pi t}} \\
T(0,t)_{\text{known}} &= \frac{Q}{b_{\text{known}} \sqrt{\pi t}}
\end{aligned}
\]

(2)

So, after the combination of the expressions (2):

\[ b_{\text{unknown}} \approx \frac{T(0,t)_{\text{known}}}{T(0,t)_{\text{unknown}}} \times b_{\text{known}} \]  

(3)

With:

\( b_{\text{unknown}} \) Effusivity sought

\( b_{\text{known}} \) Effusivity of the reference sample (here PVC : 408 JK\(^{-1}\).m\(^2\).s\(^{1/2}\))

\( T(0,t)_{\text{known}} \) Response temperature of the reference sample (PVC)

\( T(0,t)_{\text{unknown}} \) Response temperature sample

The two expressions (2) evolve according to \(-1/\sqrt{t}\) for the short times. The results on a log-log representation correspond to curves showing a -1/2 slope (Figure 8). It is therefore possible to determine \( b \) applying (3) within the temporal extent where the 1D model is valid.

The thermal diffusivity is determined using a reverse method. This parameter is then usually estimated according the goodness-of-fit the theoretical curve with the experimental one using Levenberg-Marquardt’s algorithm. Measured data such as the width of the sample are inserted in the model. The estimate is based on successive iterations from an arbitrary value to the best a value corresponding to the lack of significant difference between the two curves (Fig. 6). Two measures have been performed for each of the 10 samples; we got then ten measures for salty samples and ten measures for samples of reference without salt (Table 1).
Figure 7. Experimental device showing the samples and the camera (a).

Figure 8. Log-Log representation of the evolution in time of the cooling of references (Non-salted ones in red; PVC one in green) and NaCl contaminated ones (In blue).
3. Results and discussion

Crystallization in solution corresponds to a state change from a liquid phase to a solid phase that is accompanied by a production or a consumption of heat. In the case of crystallized hygroscopic salts, the absorption or the loss of water can correspond to a crystallographic modification that leads to a thermal energy variation too. Because of the transfer of energy that occurs during these processes, it should be observed using an infrared thermography camera.

Overheating is essentially located at the periphery of all the three studied samples. The crystallization process seems to develop itself from the edges of the samples to inside the samples. In another hand, it appears also to be from outside to inside the samples (Figure 9 to 12). As the evaporation surface is dependent from the roughness and the exchange surface of the sample, it induces variations of the thermal and the hydric and hygric conditions in depth. This leads to a crystallization gradient inside the material. More, because of the most important exchanges that occur on the edges of the wet samples with the atmosphere, the salt crystallization starts on the sample rim (Figure 12). In addition, the kinetics of appearance of overheating peaks and their intensity depend on the samples, showing the influence of the internal porous network on the speed of crystallization and intensity. At the end of the experiment the samples show a significant disparity in terms of deposits of salt which seems to confirm the previous interpretation (Figure 11).
Figure 9. At the beginning of the crystallization process.

Figure 10. During the crystallization process (thermal activity on HER sample already is visible).

Figure 11. At the end of the crystallization process (Emergence of many hot spots on the 3 samples and degradation of the surface).

Figure 12. Emergence of many hotspots during the crystallization process, observation of the germination process on the rim of the samples and beginning of the crystal growth.
The experiments show also the capacity of the stimulated infrared thermography (SIRT) to detect the presence of NaCl in stone samples. The average temperature of the reference samples (without any salt) in time is indeed significantly superior to those of salted samples at the first times of the cooling (Figures 3 and 5). This less heating of samples with salt can be explained by a lower absorption of the energy flow due to the presence of crystals on the surface that can locally modify the reflectivity of the sample.

As it is possible to differentiate a salty sample from a no-salted one, it is also possible to differentiate the salted area from the unsalted ones on a stone sample (Figures 4 and 5). The study of the temperature curves at the beginning of the cooling phase (\(t < 0.25\) sec.) confirms indeed that the salted area is significantly less heated with a same energy deposit. There is then no experimental artefact that could have occurred.

**Figure 13.** Thermal effusivity measurement.

**Figure 14.** Thermal diffusivity measurement
NaCl in high concentrations (4 %) modifies thus significantly the thermophysical properties of the stone. The data of the thermal effusivity of salted samples always is superior to non-salted ones sample 3 excepted (Figure 13). The presence of NaCl in the limestone seems also to be correlated to the increase of the thermal effusivity. This last parameter could be then an interesting indicator of the presence of salts.

As well, the thermal diffusivity shows that this physical parameter is correlated to the chemical composition of the sample (Figure 14) because the values coming from the salted samples study always are superior to non-salted ones. So, the thermal diffusivity is dependent from the presence of hygroscopic salts too. This parameter appears to be particularly sensitive to the presence of salt. As it depends on the exchange interface, the thermal effusivity should theoretically vary because of the first crystallisation of salts on the sample surface that corresponds to our observations. Thus, these observations allow leading to suppose that the presence of a hygroscopic salt in a stone modifies the both thermal effusivity and diffusivity. The ability to detect these variations should however depend also on the salt concentration.

4. Conclusion

Infrared thermography allows detecting the presence of salts in a limestone. Further experiments will be performed to try to characterize the salt concentration by the way of the thermal diffusivity and the thermal effusivity measurements. More, further work will be dedicated to determine the sensitivity of these parameters to the variations of concentration and to evaluate the influence of the experimental device on the accuracy of the measure. Last, it is possible to do observations and to characterize some transformations phases that occur during the crystallisation process. These preliminary results suggest the potential of infrared thermography in the study of salt weathering of stone and wall painting and their effects on cultural heritage objects. Experiments on the sensitivity of the technique in presence of salts in low concentrations are now in progress.

Last, the current developments are also focused on the measurement of thermal signals that a salt give when it undergoes a phase change during its (de)hydration or its deliquescence. These measurements are supposed to give information about the nature of the detected salts because of the identification of specific endothermic and exothermic signals during the crystalline arrangements changes.

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Digital Documentation of a Stone Cultural Heritage Site
Using Three-dimensional Scanning System

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Abstract

Database construction using a three-dimensional scanner is a method that can show a real-world object in a virtual space. It is popularly applied in various fields such as in researches, medical treatments, arts, industry, and cultural preservation. Its popularity is increasing because of its more precise and fast outcomes. For a unique object such as cultural property, the documentation of its status is considered one of the most important factors of its handling. Therefore, such documentation should also cover the object’s surroundings. In this study, major information on a stone pagoda, including its surroundings, was documented in three dimensions, and GPS measurements were performed to build a database for the pagoda’s geographic location information. Such data can be used as basic data for the repair and restoration of cultural treasures in the future and can be used as the content data for a study on the permanence of the stone pagoda, the provision of education data, and other purposes, database construction should be continuously enhanced.

Keywords: Digital documentation, Stone cultural heritage, Three-dimensional scanning system

1. Introduction

Database construction using a three-dimensional scanner is a method that can show a real-world object in a virtual space. It is popularly applied in various fields such as in researches, medical treatments, arts, industry, and cultural preservation. Its popularity is increasing because of its more precise and fast outcomes.

The stone pagoda that is a cultural heritage site in South Korea was precisely measured in three dimensions using a laser scanner, and such measurements, including of the pagoda’s surroundings, were recorded in original form. In addition, the obtained GPS measurement values were combined with the three-dimensional precise measurement data to build a database for the pagoda’s location information. Such data can be used as basic data for the repair and restoration of cultural heritage monument in the future, and as the content data for a study on the permanence of the stone pagoda, the provision of education data, and other purposes.

2. Site scan

Three-dimensional precise measurement of the stone pagoda was performed using a wide range scanner to achieve a less than 3mm scan precision. Such precision is considered the best that can be achieved using a wide range scanner. In the past, the receiving data volume was adjusted due to the limited data volume allowable in the program; however high-quality data can now be obtained, by the improvements on many parts of the program.

In addition, as the three-dimensional precise measurement of the stone pagoda using a laser scanner collects straight-line data, the scanner positions should be properly adjusted during its operation. In this study, the focus was made to express precisely the end points of the joint parts of the pagoda, to build a precise form information database. Wide range scanning was performed using simple temporary installations, the surrounding topography, auxiliary facilities, etc. at one- to six-stage heights, and the data were obtained from the eight basic directions.
When measuring a building such as the stone pagoda, the absolute criteria are considered important factors. The Leica Scanstation 2, C10 is equipped with an electronic level device (a dual compensator) that functions as a light waver. Therefore, it guarantees the quality of the ranges between $\pm 5'$ (minutes) with a resolution of 1” (second). Based on this function, the level criteria were applied to the pagoda.

![Figure 1](image)

**Figure 1.** Three-dimensional precise measurement of the stone pagoda. (a) Three-storied stone pagoda of ulju cheongsong temple. (b) Three-storied stone pagoda of hapcheon cheongryang temple. (c) Three-storied stone pagoda of hapcheon youngam temple.

### 3. Data processing

The original scan data were separately positioned in point cloud form. Such data should go through a process of creating an aggregate based on a criterion, which is commonly called registration. The registration process designates the same points at a minimum of three positions to conform to individual data. The two conformed data were optimized at a tolerance of 2 mm in the program.

The outcome of the aforementioned conformation appeared as an aggregate of the point cloud data. In such point cloud data, it was difficult to identify the parts where the surfaces overlapped because of the difficulties in distinguishing the front and rear points in the program. Therefore, a process converting such point cloud data to surface data was implemented. Thus, the actual data post-processing started from this process.

Before initiating the surface data processing, the existing conformation outcomes (points) were re-conformed(Figure 2). This was because the existing point data were outcomes of wide-range conformations that involved the stone pagoda and its surrounding data. First, the points collected from the stone pagoda were lined up within the program tolerance of 2 mm using commands for the optimum conformation. Then selective works followed in principle. The outcome of this study was produced by converting the individual point clouds into separate surfaces and unifying (merging) the surfaces.

![Figure 2](image)

**Figure 2.** Re-conformed (registration) process of point data.
4. Data utilization

The data, the final surfaces of which were completed, were edited to enable the drawing work. The data for the elevation, plane, and worm’s eye view of each member were manufactured based on a 1:1 scale. In addition, the three-dimensional record of the stone pagoda and its surroundings were documented with the stone pagoda, its surrounding major buildings, and the ground environment where the stone pagoda was positioned. In addition, the GPS measurement values were conformed and connected with the said records so that such information can be used in spatial information services in the future.

5. Conclusion

Three-dimensional precise measurement that targets cultural heritage monument should prioritize the accuracy of the form information, including the size information. In this study, many attempts were made to enhance the accuracy of the aforementioned parts, and this data process will become the foundation of basic studies on the safety management of stone pagodas. It is likely to produce more precise and highly usable outcomes through continuous studies, development of application equipment, and improvements and development of software in the future.

References

Study on Transparent Finishing [hobun+glue] Colour Paint of Wall Painting on Stones in the Late Koguryo Period

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Abstract
The natural inorganic binders applied to stone cultural assets have been recognized nationally and abroad. This study demonstrates, by experiment and a trial fabrication, that the transparent colour paints used for wall painting on stone in the late Koguryo Period are excellent materials for use as hardeners and as a thin-film coating substance on granite and marble. The pigment of the Ca component in the finish layer of wall paintings on lime mortar in the Koguryo Period has also been detected in the transparent finish layer of wall paintings on stone. The objective of this study is to identify the components of the pigments used in transparent finishing, and to identify the binding relationship, capabilities and functions of the stone base and pigment of transparent finishing through the experiments described below. The author of the study selected Ca(OH)$_2$, aragonite and hobun as white pigments from among eight types of calcium oxide bases (Ca components) found in nature, by taking into account the natural geological conditions in the Koguryo Period and the properties of the pigments. The author used glue and perilla oil as the vehicle (fixing agent) based on ancient documents and other evidential data. The author fabricated specimens in numbers allowed with selected pigments and vehicles by experimenting on ten types of finishing pigments in order to determine the best specimens. The results of the experiments indicate that a combination of hobun and glue solution is the most adequate pigment.

Keywords: Transparent finish colour paint, Hobun, Glue solution, Calcium carbonate, Inorganic binder

1. Introduction

Academic circles regard the techniques of wall printing on a stone base in the Late Goguryeo Period as drawing and coloring figures on stone without further processing. However, wall printing would not have survived if the prints had not been processed with a transparent finish layer on a stone base. It is hard to fix a colour paint on a stone base only with the physisorption of glue, which is thought to have been used for wall printing. It is possible that wall prints on stone in the Late Goguryeo Period have remained intact because chemical bonding was executed by a transparent finish layer.

A pigment of the Ca component of carbon carbonate in the finish layer of wall printings on lime mortar in tombs dating back to the Goguryeo Period has also been detected, as well in the transparent finish layer of wall prints on stone in tombs of the Late Goguryeo Period. Eight types of minerals consisting of calcium oxide bases of Ca component are found in nature, all of which are capable of generating calcium carbonate. However, academic societies in Japan and UNESCO that provide education courses for experts on wall prints in the Goguryeo Period, do not consider the use of calcium oxide bases as a pigment or phenomena that may occur in tomb environments.

Nor have any previous studies in Korea researched the preservation processing of wall prints to any great extent. In addition, most advanced devices are incapable of detecting the vehicles used in wall printing.

2. Objectives and methodology of study

The first objective of this study is to identify from among eight calcium oxide bases the minerals used for the transparent finish layer of wall prints on stone in the Late Goguryeo Period, and to identify the vehicles used by
searching for the best specimens. The second objective is to study the binding relationship between the stone base, the transparent finish layer, and the production process of calcium carbonate. The third objective is to identify the possibility of the inorganic binder functions by studying the capabilities and functions of the transparent finish colour paint.

<table>
<thead>
<tr>
<th>Components of pigment</th>
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<tbody>
<tr>
<td>Ca(OH)₂+ glue solution</td>
</tr>
<tr>
<td>Ca(OH)₂+ hobun + glue solution</td>
</tr>
<tr>
<td>hobun + glue solution</td>
</tr>
<tr>
<td>Aragonite + glue solution</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Types of test specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aragonite + hobun + glue solution</td>
</tr>
<tr>
<td>Ca(OH)₂+ perilla oil</td>
</tr>
<tr>
<td>hobun + perilla oil</td>
</tr>
<tr>
<td>Ca(OH)₂+ hobun + perilla oil</td>
</tr>
<tr>
<td>Aragonite + perilla oil</td>
</tr>
<tr>
<td>Aragonite + white powder + perilla oil</td>
</tr>
</tbody>
</table>

3. Conditions and methods of study for fabricating specimens

① The colour paint used for the study are [pigment + vehicle] and [pigment + adjuvant + vehicle].

② The fabricated specimens include those with good coloring dependent upon the blending ratio of colour paint, and those with poor concealment force.

③ White is proposed for clear discrimination of the binding conditions of the [stone base] and the [colour paint layer].

④ Photos of the specimens and those taken after artificial weathering are compared with the color chart of KODAK. Three specimens of good coloring are selected, and machined with sandpaper until any scratches become invisible.

⑤ The thickness of the sectional structure and the surface structure were photographed using a Digital Microscopy (Scalar, Co, Japan.), and the scale bar of the microscope photo by the Kodak Gray Scale (Licensed Product). The production of calcium carbonate was measured with an X-ray diffraction analyzer (XRD).

⑥ Colors were measured using the KURABO Color-7X for searching the CIE 1976 Lab color system, Nickerson color system, Hunter lab color system, and Munsel color system as well as the spectral reflection factor.

4. Theoretical basis and selection of materials

4.1. Stone base: granite containing biotite

4.2. Basis for selecting the transparent finish layer pigment

Eight types of minerals with calcium oxide bases are found in nature, all of which can be converted into CaCO₃ by a chemical reaction. Lime is converted into CaO and Ca(OH)₂ by firing. CaO is excluded from the experiments, since the target of the study is dry wall prints. CaCO₃ is classified into calcite, verteite, and
aragonite depending on the crystal structure. These minerals are difficult to use in wall printing in tombs, as they consist of partly-altered CaCO$_3$ from limestone. The same goes for dolomite [CaMg(CO$_3$)$_2$]. Gypsum (CaSO$_4$) is a commonly used material; however, it is altered physiochemically over time and turns darker. White powder is very soluble in water; while aragonite is soluble in acid. Based on the aforementioned conditions, the author of this study selected Ca(OH)$_2$, aragonite and white powder as the pigments for the experiments on the finish layer of wall prints in the Koguryo Period.

**Table 2.** Color characteristics of [hobun + glue] colour paint.

<table>
<thead>
<tr>
<th></th>
<th>After finishing</th>
<th>After artificial weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photo (with color chart)</strong></td>
<td><img src="image1.png" alt="Photo" /></td>
<td><img src="image2.png" alt="Photo" /></td>
</tr>
<tr>
<td><strong>Thickness of colored layer</strong></td>
<td>This specimen shows that a pigment does not permeate into the quartz section very well. The thickness of the painting layer is approx. 3.0 – 6.0 μm.</td>
<td></td>
</tr>
<tr>
<td><strong>Status of boundary surface</strong></td>
<td><img src="image3.png" alt="Status" /></td>
<td><img src="image4.png" alt="Status" /></td>
</tr>
<tr>
<td><strong>Status of permeated pigment</strong></td>
<td>Most of the sectional structure of the specimen using a [hobun+glue] solution shows good permeation in the direction of the stone base. This specimen shows the permeation of the colour paint in sections other than the quartz section. The colour paint may permeate further into other sections. The surface is generally dense, and the surface tension is high, causing a large surface angle after drying.</td>
<td>The reason for a lack of change before and after artificial weathering: Artificial weathering involved the same conditions as those in the tomb; however, condensation was not attempted in the experiments.</td>
</tr>
<tr>
<td><strong>Formation of CaCO$_3$ layer</strong></td>
<td><img src="image5.png" alt="Formation" /></td>
<td><img src="image6.png" alt="Formation" /></td>
</tr>
<tr>
<td><strong>Actual microscope</strong></td>
<td><img src="image7.png" alt="Microscope" /></td>
<td><img src="image8.png" alt="Microscope" /></td>
</tr>
<tr>
<td><strong>XRD</strong></td>
<td><img src="image9.png" alt="XRD" /></td>
<td><img src="image10.png" alt="XRD" /></td>
</tr>
<tr>
<td><strong>Creation of CaCO$_3$ layer</strong></td>
<td><img src="image11.png" alt="Creation" /></td>
<td><img src="image12.png" alt="Creation" /></td>
</tr>
<tr>
<td><strong>Change in weight</strong></td>
<td>11.30</td>
<td>11.42</td>
</tr>
<tr>
<td></td>
<td>H 89.64</td>
<td>H 96.43</td>
</tr>
</tbody>
</table>
4.3. Bases for selecting vehicle


5. Considerations and conclusions

The combination of [hobun + glue] solution produces calcium carbonate, and can be become transparent, because the environment inside a tomb always reacts with moisture. The Ca(OH)₂ or calcium carbonate of hobun is classified into primary and secondary products. The primary product is shown when a wet material is dried. hobun is an ionic solid substance of an inorganic oxide, and is both hydrophilic and highly soluble in a glue solution. The hydroxyl group produced by oxidation creates a uniform film on the interface by chemical reaction relevant to the formation of a solvent and the formation of an electric charge for ionization in liquid. The combination of [hobun + glue] solution is modified in the drying process, and changes to a structure that suppresses the oxidation reaction. As a result, the primary product of the combination is smaller than that of Ca(OH)₂.

Secondary products are mainly produced by moisture evaporation. Convection takes place due to condensation and the difference in temperature and humidity between the top and the bottom of a tomb. In particular, secondary products can be found in lime mortar wall printing in tombs where the decomposition of Ca(OH)₂ products mass of CO₂. CO₂ and water are bound to produce H₂CO₃, and carbonic acid dissolves the finish layer to separate into soluble ions. Newly produced water drops couple with each other to being about the continuous dissolution of water.

\[
\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3 \quad \text{(carbonic acid)}
\]

\[
\text{H}_2\text{CO}_3 (\text{carbonic acid}) + \text{CaCO}_3 (\text{calcium carbonate}) \rightarrow \text{Ca}^{2+} (\text{heavy carbonic acid}) + 2\text{HCO}_3^- \quad \text{(calcium solution)}
\]

When a chemical reaction takes place in the forward direction, the calcium base is dissolved, and calcium carbonate is produced in the reverse direction. The action of changing the dissolved calcium solution into calcium carbonate is performed when water loses CO₂. CO₂ is coupled with combines with water on the finish layer to produce Ca^{2+} ion, and dissolves part of the ion. When this ionic water is exposed to the air in a tomb, partial pressure of CO₂ drops to separate CO₂ from water. A major factor in producing the secondary product of calcium carbonate bases is the separation of CO₂ rather than water evaporation due to the temperature in a tomb.

Sedimentation separated into soluble ions creates a thin film on it, and settles the Ca-component pigment. When sedimentation takes place due to evaporation, the amount of the Ca component in the solution increases. The secondary product is government by location of dissolution, dewing and dissolution speed of water drop, relative humidity, and joint and fracture of granite. In addition, phasal continuity is shown by changes in the environments.

Combination of [hobun + glue] solution can be altered from a white to a transparent color depending on the
composition ratio of the colour paint. The color of granite changes to a transparent color only when finishing with translucent color. The major components of granite include feldspar (65%), quartz (30%), mica (3%), hornblende, and pyroxene. The color of granite is mainly determined by its feldspar content, while quartz does not have any effect in this respect.

References


Joseon silrok(Annals of the Joseon Dynasty), Eukwe, Deung-rok [Ex: Seonwonjeon Hall of Changdeokgung Palace and Gyeonbokgung Palace(北闕眞殿丹靑及假漆所入 ‘8 法油, 2 明油.)]


Nihon Shoki, 692, Suiko Tenno 18th year. (Koguryo Damjing : soot glue)


Material Characteristics and Provenance Interpretation at the Baegak and Naksan Area of Seoul City Wall

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Abstract

Seoul City Wall was the defense facility of Hanyang, which is the present-day Seoul, and was the Capital City of the Joseon Dynasty (1392 to 1910). It is a landmark of Seoul and has been designated as part of a tentative list of world heritage sites in 2012. Seoul City Wall was partly destroyed during modern times, but recent restoration efforts are aimed at returning it to its original condition. In this study, we investigate the material properties and interpret the provenance for partial sections of Seoul City Wall that are scheduled for restoration. Our research has revealed that stones of the fortress are composed mainly of pinkish granite, reddish granite, leucocratic granite, fine-grained granite, aplite, and banded gneiss. We have carried out provenance interpretation on the basis of old documents, geological maps, and material properties. These results will contribute to the restoration of Seoul City Wall.

Keywords: Seoul City Wall, Granite, Material properties, Provenance interpretation

1. Introduction

Seoul City Wall was built in 1396 to defend Hanyang, which is the present-day Seoul. Initially, the Seoul City Wall was built from earth and stone to encompass Bugaksan, Naksan, Namsan, and Inwangsan; the suffix “san” means “mountain.” Since then, the earthen wall was gradually rebuilt from stone to assume its present shape. In the process of modernization, however, Seoul City Wall was partly destroyed by development measures. Thus, in order to revive its original shape, restoration work is necessary, and appropriate restoration is paramount for authenticity.

During the past decade in Korea, a considerable number of studies has been conducted on provenance interpretation for stone cultural heritages (Lee et al., 2007; Lee et al., 2009; Kim et al., 2013). However, Seoul City Wall has not attempted to interpret the provenance of the stones for the destroyed partial sections of scheduled for restoration. Therefore, in the present study, we conducted a detailed petrological investigation these wall sections, and we classify the constituent rocks by which dominant rock type is based on its percentage. In addition, the provenance of stone was interpreted on the basis of the result of geological, petrological, mineralogical, and geochemical analyses on Seoul City Wall and its surrounding rocks.

2. Current states

The total length of Seoul City Wall is approximately 18.6 km, and it can be divided into six sections including Baegak (which is the former name of Bugak), Naksan, Heunginjimun, Mokmyeok, Sungnyemun, and Inwang. These sections begin at the top of the Bugaksan, or the Bugak Mountain, and are subdivided into 97 sections. This division method originated in the King Tae Jo period during the Joseon Dynasty. The length of each section is approximately 192 m, which is divided in subsection halves referred to as 01 and 02.

Of these sections, three are scheduled for restoration and are the subjects of this study. Two sections are located in the Baegak area, which include 10-02 (10 m) and 21-01 (86 m), and one is located in the Naksan area 32-02 (21 m). These sections consist mostly of granite with slightly different characteristics.
3. Petrological characteristics

The studied sections of Seoul City Wall are located in different areas and are distinguished by construction type, construction period, and rock type. Therefore, field occurrences and polarization microscope analysis were conducted to classify the mineral composition of each section's rock.

The stones of the fortress observed in Baegak area 10-02 are pinkish granite, reddish granite, leucocratic granite, and aplite. Moreover, additional units of pinkish granite and light gray granite were used for the most recent restoration materials. Similarly, Baegak area 21-02 is composed of pinkish granite, reddish granite, leucocratic granite, fine-grained granite, aplite, and additional pinkish granite used for restoration material. The pinkish granite consists mainly of quartz, plagioclase, plagioclase, and biotite (Figure 1). The reddish granite consists of quartz, perthite, plagioclase, and biotite (Figure 1). The leucocratic granite consists of perthite and plagioclase characterized by sericitization. The pinkish granite used as restoration material also included perthitic alkali feldspar, plagioclase with zonal structures, microcline with twin lattices, and sericite. The restoration material of Baegak area 21-01 includes only pinkish granite, contrary to that in Baegak area 10-02.

Naksan area 32-02 consists of pinkish granite and fine-grained granite and does not contain reddish granite or leucocratic granite. The red color of the pinkish granite was lighter than the pinkish granite in the Baegak area. Measurement of the magnetic susceptibility, for petrological analysis, was conducted on Seoul City Wall to interpret the provenances of its stones. The results indicate that the magnetic susceptibilities of the stones differ among rock types at the same location (Uchida et al., 2007).

4. Provenance interpretation

In order to clarify the origins of various rock types used to constructed Seoul City Wall, detailed analyses were conducted to determine potential geopolitical importance based on old maps, geological maps, topographic maps, and aerial photographs. From those results, it was interpreted that the most probable provenances were Bugaksan, Naksan, Namsan, Inwangsan, and a mountain range surrounding Seoul City Wall. Thus, mineralogical characteristics and geochemical evolution paths were analyzed to investigate the homogeneity of stones between Seoul City Wall and the presumed provenance.

The stones of Seoul City Wall and presumed provenance were determined to consist of the same rock-forming minerals (Figure 2) and showed very similar geochemical behavior characteristics and evolution trend in each rock type. This result indicates that Seoul City Wall was built from stones of nearby mountains from the perspective of petrology. Each provenance of the studied areas was interpreted by comparing petrographic features and magnetic susceptibility of Baegak area 10-02, Baegak area 10-02, Naksan area 32-02, and their surroundings.
Figure 2. Polarizing microphotographs of granite from the research areas. (A) Pinkish granite of Baegak area 10-02, (B) Pinkish granite (restoration material) of Baegak area 10-02, (C) Pinkish granite of Baegak area 21-01, (D) Reddish granite of Baegak area 21-01, (E) Leucocratic granite of Baegak area 21-01, (F) Pinkish granite (restoration material) of Baegak area 21-01, (G) Pinkish granite of Naksan area 21-01, (H) Lightgray biotite granite of Naksan area 21-01.

5. Conclusions

Baegak area 10-02 (10 m), 21-01 (86 m), and Naksan area (21 m) of Seoul City Wall consist of pinkish granite, reddish granite, leucocratic granite, fine-grained granite, and aplite. The stones that were used as the materials of recent restoration include pinkish granite and light gray granite. These stones consist mainly of quartz, akali-feldspar such as orthoclase and microcline, plagioclase, and biotite, and polarization microscope analysis revealed very similar mineral compositions. Detailed survey for provenance interpretation was conducted around Seoul in which the source area and transportation routes of stones were interpreted on the basis of research results of old document and petrological studies.

As a result, granite of Baegak area 10-02 was determined to be similar to the granite of Bugaksan by occurrence and magnetic susceptibility. In addition, the pinkish granite and reddish granite of Baegak area 21-01 were taken from nearby Naksan during the reign of King Sejong. The pinkish granite and reddish granite of Baegak area 21-01 were taken from Bukhansan during the reign of King Sukchong, as determined through old documents and magnetic susceptibility analysis. The pinkish granite of Naksan area 32-02 is originated from Bukhansan.

References


Testing of Treatment Effects of Nano Sols on Selected Porous Historic Materials

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Abstract

Efficient nano materials for consolidation, cleaning and hydrophobization of porous historic materials have been developed in several European and national research projects. The authors have developed some new and have enhanced some existing experimental techniques for testing the effects of such conservation agents on historic materials in laboratory as well as in situ. The contribution presents in a comparative way namely consolidation effects of commercially available nano lime product CaLoSiL containing suspension of calcium hydroxide nano particles in different alcohols on porous stone or lime mortar. The resulting effects of these products on selected types of substrates have been assessed using specially developed non-standard testing methods which accommodated testing of unknown penetration abilities and the need to measure very subtle strengthening effects in laboratory, as well as on site. The innovative methods enabled to carry out a comparative study of the effect of various consolidation agents, taking advantage of destructive tests on purposely designed thin walled mortar elements, compacted sand or dry crashed stone specimens, small size stone specimens and thin plates. The influence of the quality of the substrate is well visible and helps to select "standard" materials for such comparative testing. Efficiency of these new nano materials has been measured by relation to effects of lime or barium water which were recommended consolidating agents in recent decades. Further, a non-destructive test called ‘the peeling method’, and a semi-automatic micro-tube device which measures water uptake have been devised for in situ testing of historic plaster. The poster further demonstrates potential of such non-traditional and affordable methods for approximate assessment of mechanical characteristics from non-mechanical data.

Keywords: Porous historic materials, Nano lime, Consolidation, Non-standard testing

1. Introduction

Within the EC FP7 STONECORE project efficient nano technologies have been developed and tested, namely for consolidation of porous stone or lime mortar by application of a commercially available product CaLoSiL® containing suspension of calcium hydroxide nano particles in different alcohols (Drdácký et al., 2009). Various types of CaLoSiL®, with high and variable concentrations of Ca(OH)2 (15 g/ litre, 25 g/ litre or 50 g/ litre) suspended in different alcohols (ethyl-alcohol, isopropyl-alcohol or n-propyl-alcohol) were tested as potential strengthening agents for damaged surfaces. The resulting effects of these products on selected types of substrates have been evaluated using specially developed non-standard testing methods which accommodated testing of unknown penetration abilities and the need to measure very subtle strengthening effects in laboratory, as well as on site. The innovative methods enabled to carry out a comparative study of the effect of various consolidation agents, taking advantage of destructive tests on purposely designed thin walled mortar elements, compacted sand or dry crashed stone specimens, small size stone specimens and thin plates.
2. Testing of consolidated substrates and results

The tested substrates, the testing methodology and results are presented in a tabular form, which gives a better overview. A non-destructive test called "peeling method" for assessment of consolidation material characteristics, and a semi-automatic micro-tube device which measures water uptake have been devised for in situ testing of historic plaster which is another substrate included in the study.

Compacted sand specimens were prepared from a mixture of sand, marble powder (St. Margaretten, Austria) and water (Drdácký et al). Their very fragile nature required to apply so called prosthesis method for preparation of properly long test specimens for bending.

Figure 1. Experimental set-up for three-point bending (left), tension (centre) and compression (right) tests.

Figure 2. Strengthening effects on the compacted sand after 5 and 10 cycles of impregnation by CaLoSiL 25.

Lean lime mortar specimens were prepared from a mixture of river sand and aerial lime in ratio of 9 : 1 (Drdácký and Slížková, 2012). The mortar enabled to produce thin-walled flat and tubular specimens with excellent penetration capacity.

Figure 3. Non-standard thin walled lean lime mortar specimens - plates for tension (left) and tubes for compression (centre) tests, and an example of treatment of the tubular thin-walled specimens.
**Figure 4.** Strengthening effects on the lean lime mortar after various cycles of impregnation by various nano-lime agents (CaLoSiL 15 and CaLoSiL 25) - increase of tension strengths (left) and compression strengths (right).

_CaLoSiL_ agents were prepared from a mixture of river sand and aerial lime in ratios of 4 : 1, 6 : 1 and 9 : 1 (Moreau et al., 2010), and used for testing the influence of the number of applications up to ten cycles of repetition.

**Figure 5.** Experimental set-up for three-point bending (left) and compression (right) tests on the broken halves of the lime mortar beams after the bending tests.

**Figure 6.** Strengthening effects on lime mortars - the influence of number of CaLoSiL 25 treatment cycles.
Maastricht limestone is a soft bioclastic calcarenite of Upper Cretaceous age, from the area between Belgium and The Netherlands (Slžková and Frankeová, 2014). Strengthening effects have been tested in various depths under the treated surface.

**Figure 7.** Cutting pattern of the impregnated specimen (left) and the test arrangements (centre and right).

**Figure 8.** Depth profiles of changed mechanical characteristics of a soft limestone after nano-lime treatment.

Kutná Hora limestone is very nonhomogenous detritic stone with a highly variable porosity and varying mechanical characteristics (Drdácký et al.). The tests show strengthening effects on a rather compact, sound and strong stone.

**Figure 9.** Compression test set-up (left) and a typical structure of the Kutná Hora limestone.

**Figure 10.** Strengthening effects of various nano-lime products and cycles on the Kutná Hora limestone.
Ancient lime plaster in situ  Medieval monastery renders made in three different centuries have been successfully treated with the CaLoSiL agents and compared to one ethylsilicate application (Bryseejn et al., 2010).

Figure 11. In situ measurements of water uptake (left) and subsurface cohesion (right) characteristics.

Figure 12. Water permeability effects of the nano-lime (CaLoSiL) treatment on a historic render compared to the ethylsilicate impregnation effect (left). Principle of peeling tests evaluation (centre) and the measured data on a historic render after the nano-lime treatments.

3. Conclusion

The compacted fine aggregate model materials demonstrated very well the capacity of a consolidation power of the CaLoSiL nano lime agents. Treated compacted sand or crushed stone, modelling deteriorated stone or degraded mortars and plasters, attained consolidation or strengthening effects of several orders and the original very low strength could be increased up to nearly thirty times higher values. On the other hand, impregnation of a heterogenous but rather strong limestone in all tested treatment modes caused from a slight to good consolidation effect. However, the applicability of lime nano-sols has limits which depend on the ratio of the nanoparticles to the size of the substrate pores. Consolidation of lime mortars attained significant improvements after both the laboratory as well as in situ application tests. The both newly developed non-destructive methods for mortar and stone characterization provide results correlating with strengths (Drdácký and Slížková, 2013).

Acknowledgement

This poster was created with support from the Ministry of Culture NAKI project DF11P01OVV012, and from the Czech Grant Agency grant No. P105/12/G059.
References


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