NATURAL STONE MONITORING – INVESTIGATION METHODS FOR A RELIABLE EVALUATION OF THE EFFECTIVENESS OF CONSERVATION MEASURES

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Abstract

Because monuments are not always regularly monitored, a reduction of conservation effectiveness and initial damage can be easily overlooked. Consequently, expensive and comprehensive measures are necessary, which are associated with high material input, enormous costs and, therefore, with a waste of resources. Moreover, a loss of historic substance is very likely. To ensure sustainability of stone conservation, the present situation has to be improved by introducing a methodology for quality control of all future treatments. Investigation methods for a reliable evaluation of material alterations and stone conservation effectiveness were determined in a project supported by the German Environmental Foundation. Fourteen non-destructive and minimally invasive measuring methods, among them most importantly the capillary water absorption with Karsten Tube and peel-off and abrasion resistance, were tested regarding their applicability for reliable monitoring. Clear directives for performing these tests were established which provide standardised measuring procedures also for long-term future investigations. Altogether 30 well documented stone objects - representing different materials and conservation methods - were analysed. Clear trends could be found regarding the sustainability of strengthening and hydrophobic treatments.

Currently the compiled standardized testing methodology, including a uniform documentation system, is being adapted into a guideline of the International Association for Science and Technology of Building Maintenance and the Preservation of Monuments (WTA), to emphasize the general necessity of monitoring in the field of monument preservation and to support the application of the methodology as a standard for natural stone monitoring.

Keywords: monitoring, natural stone, conservation, methodology, sustainability, evaluation of treatment

1. Introduction

Natural stone and also other mineral building materials are subject to weathering processes, which also continue after conservation. The objects are still exposed to anthropogenic environmental impacts such as particulate matter, nitrogen oxides, ozone and sulphur dioxide. However, sustainability of conservation measures depends on many other parameters, which often remain unconsidered in this context. These are, for instance, the prior status, the various sandstone types (e.g. rich in clay minerals), salt load, exposition (orientation, height) and condition of the joints up to the quality and time of conservation measure. All these factors can lead to a decrease of the effectiveness of conservation over time. Due to a lack of regular controls the reduction of conservation effectiveness and initial damage can be easily overlooked. Consequently original substance is put at risk and expensive and comprehensive measures are necessary, which are associated with high material input, enormous expense and, therefore, with a waste of resources. An important problem in this context is on one hand the limited financial resources. On the other hand a lack of awareness regarding the necessity and tangible benefits of monitoring impedes the introduction of control and maintenance intervals. Product promises by different companies assuring durability of 10 and more years probably also play an essential role. Often it is also assumed that restorative measures must last forever. Afterwards the objects are left to themselves until the extent of damage has reached a critical dimension. An alternative to comprehensive measures would be a system of a continuous monitoring and maintenance. In the majority of cases early interventions would keep the necessary measures small and save costs. However, the early stages of damage progression are often not even noticeable. Therefore scientific investigations may be necessary for the monitoring of natural stone or other architectural surfaces. Standardised investigation methods are essential to observe the weathering process systematically and, if necessary, take the required measures. Investigation methods for a reliable evaluation of material alterations and stone conservation effectiveness were determined in a nationwide project supported by the German Environmental Foundation. To develop an appropriate methodology, about 30 stone objects were examined in the framework of this research program. Conservation measures on these objects had been carried out in a time span of 5 to 30 years previous to the monitoring. The primary aim of the project was to choose previously established investigation methods from a lot of former research projects regarding their applicability for objective monitoring. For long-term monitoring, in particular, the reproducibility and the comparability of measurements play an important role. Consistent execution and examination directives were a primary requirement within the project. Over the long term these methods provide reliable results independent of the measuring person. Moreover, a standardised system of monitoring - e.g. definition of uniform mapping- and documentation standards must be included. For long-term observations of course no invasive and material-intensive methods can be applied. The application of non-destructive and minimally invasive measuring methods is in the focus. Within the project all objects were examined as examples using the established system and methodology.

Furthermore, the project focused on the long-term effects of conservation methods and materials, stone type or application. Recommendations were also elaborated upon regarding future control intervals and renewed conservation. Important conclusions concerning the long-term stability of conservation materials and the compatibility of specific stone types and certain conservation methods could be drawn. The experiences and data were also used for the development of a guideline for the monitoring of monuments made of natural stone.

2. Investigation methodology

Here investigation and measuring methods that were used in the context of the DBU project on natural stone monitoring are presented. Most of these methods have already been in use for a long time for investigations of natural stones. The methods concerned were examined in the context of the project to assess their applicability for reliable monitoring.

The project partner agreed upon the standardized procedure for the examination of the selected cultural heritage objects:

1. Data compilation from old files and from documentation of previous preservation measures
2. Visual inspection of the buildings and monuments
3. Definition of representative reference areas for monitoring and further investigation
4. Mapping of stone varieties, conservation measures and damage
5. Testing of physical parameters indicating the weathering state of stone
6. Evaluation of the object

Fourteen non-destructive and minimally invasive measuring methods were tested, among them most importantly capillary water absorption with the Karsten pipe, micro-drilling resistance, peel-off resistance (tape test and abrasion test with brush) as well as ultrasonic velocity and detection of delamination/scaling with resonance sensing bar or infrared thermography. Clear directives for performing these tests were established, which also provide standardized measuring procedures for long-term future investigations. In this context, open questions are also to be addressed concerning limitations of the methods and the evaluation.

For the assessment of conservation measures in the past, drill cores of the original material were often taken. From these samples a lot of results are available regarding the previous conditions to which one could refer within the monitoring. Although measurements of Biaxial-Flexural-Strength and E-Modulus, which were accomplished in this context, provide reliable and reproducible results, nowadays these tests are not suitable for monitoring procedures because of the necessity of sampling. The same applies to ultrasonic measurements regarding the penetration efficiency or the degree of weathering along a depth profile (drill cores). But this method can be perfectly used for non-destructive transmission measurements on sculptures, for instance.

2.1 Mapping

An important research method in the context of monitoring natural stones and other mineral building materials is the mapping of different phenomena. The graphic visualization of the damage is helpful for recognizing and evaluating damage processes and their origins and causes and to clarify interdependence. Therefore mapping and photo documentation must be part of an adequate survey which is the basis for all later investigations. For each object it must be decided which subjects and phenomena are necessary to map. Within the DBU project the basis for the damage mapping was the ISCS glossary (2010). The basis of the legend used is the slightly modified VDI recommendation 3798 (1998) for documentation because it offers a broad spectrum of graphic visualizations for different objects, stones and weathering phenomena. One goal of the working group is the general implementation of this mapping legend in the field of natural stone monitoring.

The scale of the mapping must be adapted to the object. In the digital evaluation, true-to-scale mappings allow surface- and length-related conclusions. The multitude of mapping topics requires them to be clearly distinguished visually to ensure good readability. Beyond that a mapping needs the written explanation of an experienced investigator and a damage glossary, which supports the digital mapping photographically.

2.2 Investigation of water uptake

2.2.1 Capillary water absorption

In the context of natural stone monitoring the determination of capillary water absorption is most importantly because lots of non-destructive measurements can be carried out again and again. Normally the Karsten pipe is used for capillary water absorption measurements. Two programs are available for evaluation of the measuring data: both are based on Microsoft Excel®. One has been used satisfactorily for many years (the Calkarow program in the current version 3.2 from Wendler and Pfefferkorn) and there is now the newer evaluation algorithm of Niemeyer (2010). Both programs are based on the supposition of an even, direction-independent migration of water in the porous structure of the stone material according to capillary rules. As Calkarow has generally been used for many years and sometimes unrealistic water-absorption capacities and b-values are the result, the assessment of the w-value by Niemeyer is a new approach. With this program the w-value is not only determined mathematically as with the Calkarow program, but visually assessed by comparison of the measured values portrayed on a graph with several generated graphs. For more detailed information see the publication Leitfaden Naturstein-Monitoring (The results of the DBU-project are published in this “Guideline for Natural Stone Monitoring,” issued in 2010 by Fraunhofer IRB Verlag Stuttgart (Auras et al 2010)). On sculptures with small-scale surfaces, the Mirowski pipe was used in the project. This pipe also consists of a graded tube, though the upper end is sealed airtight. In the lower end there is a sponge. After the tube is filled with water, the sponge is brought into contact with the stone surface. For the application of the tube to the stone surface, a supplied device consisting of a clamp and two needles in combination with a rubber band (see fig. 1) or a lab-rack is used. The developing lower pressure is compensated by the air supply through the sponge. As an effect of water absorption, a wet zone forms around the pipe. From its diameter, the water absorption degree and direction can be determined. Comparing the dampened volume (V0) with the amount of the absorbed liquid (Vf) gives the volume-related liquid absorption capacity (Fv) using the equation Fv=Vf*100/V0. In contrast to the Karsten measurement, for the Mirowski pipe the amount of water absorbed is proportional to the duration of soaking. Thus, the calculation of a water absorption value per hour [ml/h] is possible. This value is not directly comparable with the results of Karsten measurements (w-value).

The application of Karsten pipes is combined with the use of solvent-containing putty. To fix the tubes on sanding surfaces during the measuring period (60 min) is often complicated. Furthermore, sometimes residues from the putty stay on the surface and must even be retouched subsequently. Regarding these two circumstances Mirowski measurements prove to be a good alternative to Karsten measurements, even though their results are not comparable to w-values, which again are related to the assessment criteria set out below (see Tab. 2).

Figure 1. Example of application of the Mirowski tube (photo R. Wennemer)

2.3 Investigation of strength parameters

In order to detect the strength alteration within a long-term monitoring programme, different methods are suitable to different degrees. There are for instance the ultrasonic velocity, drilling resistance and of course peel-off resistance, particularly for determination of the strength near the surface. Within the project this method, which is described below in detail, was also revised regarding evaluation modes. Furthermore, a quite simple test for determining the abrasion was developed. The aim was to create a test with an easy manageability. The method was applied on almost every investigated object within the project. It remains to be seen if this test will develop towards a standardised method. Depending on the executing person, environmental conditions and also the type of the brush, remarkable differences in the results can occur. Nevertheless, the test is absolutely suitable to getting orienting results about the development of the surface strength over a long time. Later this test will be described in detail.

2.3.1 Abrasion test using a brush

For the determination of granular disintegration near the surface, the abrasion of the loose surface with a small brush has been tested (see fig. 2). Therefore, a defined surface area (template 10x10 cm for masonry stone surfaces, 5x5 cm for sculptures) was brushed off with a brush of exactly defined stiffness (da Vinci No. 14, series of 111). The brush was swept 10 times vertically and 10 times horizontally across the test surface. The released material was filled in a lockable box. The weighing took place after drying the material at 60°C. For the evaluation of the measurement, the quantity of the brushed-off material measured in grams is related to the test area (100 cm² or 25 cm²). Particularly on sculptures, a conversion of the result to kg/m² leads to an overestimation of the extent of the damage, because not the whole surface of the sculpture is affected by the same disintegration process.

Figure 2. Utensils for the abrasion test

Using this test, an objective description of the degree of granular disintegration is possible. A precise evaluation with respect to removed or disintegrated grain-layers is problematic. However, from the quantity of the brushed off grains and the bulk density of the respective stone material, the thickness of the removed layer can be calculated. On the assumption of an average grain size (e.g. Grimm, 1990) at least the number of grain layers could be approximately calculated. Problems with this evaluation algorithm exist when vegetation or biological crusts lead to an incorrect result. For magmatic stones such as Tuff and Trachyte no average grain size can be determined, so that this calculation cannot be applied. The reliability of the evaluation regarding the grain-layers must still be verified by further applications.

2.3.2 Peel-off resistance

This method, called Power Strip® test, is also already established in the practice of monument preservation. Power Strip® tape is applied to the natural stone surface. After the strip is peeled off, the quality of cohesion of the superficial grain layers can be assessed by the number of adhering particles. A spring balance is used for determining the required tension strength. Spring balances with a resolution of 25 N maximum are sufficient because tension strength above 20 N is not to be expected. At the beginning, the surface is only lightly blown off, not abraded. Then, a Power Strip® 20mm x 50 mm is fixed evenly to the surface. Afterwards, the strip is peeled off by the spring balance that is fixed to the tape by a clamp. The direction of tension is either perpendicular or parallel to the surface. On disintegrated surfaces, the test is repeated on the same measuring field, several times if necessary. Also on surfaces covered by dirt or biological growth several tension tests have to be applied in order to assess the quality of cohesion correctly. The test is finished when no more particles can be removed. Then the cohesion of the stone exceeds the adhesive strength of the Power Strip® or the tension strength is almost constant. The number of tests and the respective determined strengths result in a kind of strength profile. The peel-off resistance results from the tension strength and the width of the Power Strip® (see equation 1). The peeling tension w is determined as a quotient of the force w which is necessary to peel off the strip (width b and length l) from the stone surface. For the peel-off resistance the following equation is applied:

$$W=F/b \text{ [N/mm]} \qquad [1]$$

Additionally the tapes can be weighed or the degree of grain coverage can be estimated. Temperature has an influence on the test. Therefore, measurements should be made only between 15 and 25 °C. Furthermore, the tests should be performed only on dry surfaces.

2.4 Other investigation methods

Beside the methods described above, which were applied on almost every examined object within the project and which somehow belongs to a „Monitoring-standard“, other methods needed for special problems - adapted to the requirements of monitoring - were applied, as for instance tests for the investigation of delaminations and colour changes were performed.

2.4.1 IR Thermography

On some objects, passive and active infrared (IR) thermography was used for detecting delaminations and the monitoring of backfill. This method is contactless and non-destructive. Investigations of a large façade area using passive IR thermography allow only limited interpretation of stone damage. But with active IR thermography, delaminations can be detected clearly due to their thermal activation. For the investigated objects a comparison with the damage mapping shows a clear correspondence with the IR thermography.

The monitoring with IR thermography should take place at reference areas with different degrees of exposure and building situations.

Furthermore, the **resonance sound detector** was used for the non-destructive detection of delaminations and hollow areas. The detector consists of a solid metal ball (diameter 20 mm) attached to a removable bar. The metal ball is moved in lines over the surface. Vibrations generated in this context lead to a resonance of the air layers in defects beneath the surface. Therefore cavities can be detected acoustically. The boundary between delamination and stone is marked in the scale mapping. The documentation of hollow defects allows an overview of hidden conservation problems.

2.4.2 Colour measurements

As a further monitoring instrument in addition to colour charts, a spectrophotometer was also used and is suitable for the investigations of homogeneous substrates such as painted coatings or very uniform stones e.g. white marble. Colour changes can be monitored and recorded over a long interval.

3. Long-term experience with preservation and restoration methods

Altogether about 30 well-documented stone objects, representing different materials and conservation methods, were analysed as part of the project. On every object different combinations of standardized tests were performed by experienced restorers and scientists. The comparison of all data from all objects provided insight into the long-term effects of various conservation methods and materials. Clear trends could be found regarding the sustainability of consolidating and water-repellent treatments. A general classification had to be developed for the evaluation of materials and methods of conservation. Furthermore it is linked to recommendation regarding the necessity of new monitoring or conservation steps (see Tab. 1). From this general classification specific criteria were derived for several conservation methods (see Tab. 2).

3.1 Water-repellent treatment

In the project some objects were investigated which had been treated in the past with a water-repellent agent, in some cases after a consolidating treatment. For regular and non-destructive monitoring, the assessment of the effectiveness of a water-repellent treatment is mainly based on the capillary water uptake coefficient w. Therefore, the w-value also forms the basis for evaluation in the project. As outlined long before by other authors (e.g. Wendler & Snethlage, 1988), the efficiency of hydrophobic treatments declines with time. In accordance with the Leitfaden Steinkonservierung (Snethlage 2008) and the requirements established by Snethlage & Wendler (1996), a w-value < 0.1 $kg/m^2\sqrt{h}$ is regarded as necessary for an effective reduction of the capillary water absorption of the building material. Otherwise the pore structure can still take up considerable quantities of water, which may lead to permanent moisture content and salt mobilization. Slightly deviating from Wendler & Snethlage (1988) within our project, a classification for the state of a water-repellent treatment was compiled and used (see Tab. 2). The effectiveness of a water-repellent treatment is insufficient when the water absorption coefficient exceeds 0.5 $kg/m^2\sqrt{h}$. This value refers to the DIN EN 1062 (2004-2008) and represents the upper limit for a still acceptable water-repelling effect. In this case a water-repellent re-treatment for the protection of the object should be considered (Meinhardt-Degen & Snethlage 2004). Heavy precipitation on such objects would lead to an accumulation of humidity because the moisture cannot completely evaporate during the drying periods.

Regarding these requirements, four of the seven investigated objects show very good or sufficient water repellency against rain load. Objects made of Elbsandstone (Cottaer variety) (quartzitic) still have very good to satisfactory effectiveness of the water-repellent treatment (Notes 1 and 3, see Table 2). The values for the Postaer variety of Elbsandstone are at the upper limit of a still acceptable water-repellent effect (Note 3, see Table 2). The varieties of the carbonatic Regensburger Greensandstone at the Alte Pinakothek, Munich, represent an effective water-repellent treatment with values between 0.12 and 0.22 $kg/^{2}m\sqrt{h}$. The critical w-value of 0.5 $kg/m^{2}\sqrt{h}$ is exceeded only at one of nearly 240 measuring points (Note 2, see Table 2).

A dependency on the treated stone material became apparent regarding the durability of water-repellent treatments. Siliceous sandstones exhibit a durable effect of the water-repellent treatments. In the case of clay-containing sandstones, the durability of water-repellent treatments is very limited. So, for example, after 15 years of exposure the w-values of the Schilfsandstone of Birkenfeld Monastery are similar to those of the untreated stone. Also, the water-repellent treatment applied to the Schilfsandstones of Schillingfürst castle in the 1970s and 1980s is no longer effective.

As expected, the results obtained show that the durability of water-repellent treatment is dependent on the type of stone. If the penetration of the water-repellent agent is not sufficiently deep, contour scales may detach from the surface, as happened on the west gable of Birkenfeld Monastery. The WTA working group which issued WTA data sheet E-3-17 (2010) recommends water-repellent treatment only for stones with a capillary water absorption coefficient higher than 1 $kg/m^{2}\sqrt{h}$. It also provides appropriate test procedures to derive the necessary penetration depth of the water-repellent agent in order to ensure good effectiveness and durability. A general recommendation for or against water-repellent treatment can, of course, not be given; however, water-repellent treatment should be carried out only on façades that are really exposed to direct rain.

3.2 Consolidating treatment

On many of the investigated objects, stone consolidating treatment with silicic acid ester had already been carried out. A comparison of the test results is limited because many factors must be considered. As expected, concerning the durability of these measures, a tendency to a degradation of the effectiveness with increasing treatment age can be observed. In most cases the decrease of the strengthening effect is observed on stones contaminated by soluble salts.

Full impregnation with PMMA ("Ibach Method") was considered in the project as well. For the evaluation both problematic stone materials and marble were investigated using ultrasonic velocity measurements. As a result the procedure proved very good in the case of marble sculptures. Sandstone objects which were treated in the infancy of this method in the 1980s often show cracks because of insufficient penetration of the PMMA. The method proved to stabilize durably even very decayed sandstone surfaces for more than 20 years exposure time, also in the case of clay-rich sandstones. However, intensive cracking occurred in cases when, due to insufficient drying or cooling times, the monomer MMA was unable to penetrate to the core of the object. Consequently, damage to objects fully impregnated with PMMA is rather a matter of precise conduct of the impregnation process than a general failure of the method. In every case the decision to subject an object to PMMA full impregnation must be discussed thoroughly and reasoned.

3.3 Stone repair mortars

In the course of preservation and restoration work, stone repair mortars also play an important role. Depending on the stone material, the kind and extent of damage as well as technical requirements, different products are used. Independently of the material composition, different long-term behaviours occur. Mortars which run out thinly at their edges tend to form delaminations and cracks. In the case of dense repair mortars which are not sufficiently adapted to the original stone material, salt and moisture transport processes in the masonry run through the adjacent stones, where substantial damage can result. This observation underlines the importance of ensuring the compatibility of stone and repair mortar with regard to the decisive mechanical and moisture transport parameters (Snethlage 2008, 2011). A correlation between mortar composition and lifetime is currently impossible to derive, because the available database is too small to interpret the influences of the individual method of application, mortar compositions, stone parameters as well as object-specific conditions like ambient climate or the salt content of the masonry. (Due to these influencing factors no correlation between mortars' binding material, type of stone or time could be found.)

4. Conclusions

Natural stone monitoring is of special importance in monument preservation. For reliable monitoring, investigation procedures are recommended whose methodology and evaluation are standardized and also still applicable after decades. Special attention has been given to the methods selected being inexpensive and easy to conduct.

For the evaluation of measures in stone conservation and restoration, a general evaluation code was developed, from which recommendations for measurements and appropriate time intervals can be derived (see Tab. 1 and 2).

Natural stone monitoring provides information about:

- durability of the stone varieties as a function of exposure and former treatment;
- effectiveness and durability of substances/measures for the preservation and restoration;
- material and object-specific definition of maintenance cycles for long-term preservation and cost control.

Apart from material-relevant aspects and information regarding maintenance cycles, there are also effects which can contribute to the cost control of the building maintenance as well as to cost saving:

- detection of necessary and avoidance of unnecessary and/or harmful measures;
- early detection of damage processes in progress;
- precautions against formation of major damage, whose repair is far more expensive than regular monitoring and maintenance.

Monitoring, therefore, should be a constant in the maintenance of historic buildings.

Table 1. General classification based on the degree of new damage after conservation and Recommendations for further measures

Performance*	General classification / Degree of new damage	Recommended measures	Time span
1	no new damage detected	Monitoring	after 5 years
2	slight damage or detection of damage potential	Monitoring	after 3 years
3	medium damage	repair or renewed conservation	within 3 years
4	heavy damage	urgent repair	immediately
		or short term repair	within 1 year
5	heavy damage and loss of function (e.g. statics, water drainage)	urgent repair	immediately

(*In the case of unsatisfactory adjustment in the material indices (e.g. over-strengthening), if necessary downgrading of the evaluation)

Table 2. Classification of the long-term performance of conservation materials

Performance	General classification /Degree of new damage	Classification		
		Hydrophobic Impregnation	Restoration Mortars	Strengthening (Ethyl Silicate)
1	no new damage detected	$w_{mean} < 0.1$	No new damage	No new damage
2	slight damage or detection of damage potential	$w_{mean} < 0.2$	Slight damage (for example sanding and crack formation at < 10 % of mortar) or no damage but bad match or physical properties	Slight damage in form of sanding caused by local decrease of strengthening or no damage but evidence for disadvantageous strengthening (bad strength profile)
3	medium damage	$w_{mean} < 0.5$ and $w_{max} <1.0$	Distinct damage (10-25 % of the mortar with cracks or local detachments without danger of loss of pieces)	Distinct decrease of strengthening (sanding or flaking at 10-25 % of the treated area)
4	heavy damage	$w_{mean} < 0.5$ and $w_{max} >1.0$	Severe damage (> 25 % of mortar with sanding, cracks or local detachments without danger of loss of pieces)	Severe decrease of strengthening (sanding or flaking at > 25 % of the treated area)
5	heavy damage and loss of function (e.g. statics, water drainage)	$w_{mean} > 0.5$	Extreme damage (> 50 % of mortar) or danger of loss of pieces)	Heavy weathering phenomena with loss of surface or attenuation of the load bearing capacity

(w = water absorption coefficient [kg/m²√h])

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References

Auras M., Meinhardt, J. & Snethlage R (eds.) 2010. Leitfaden Naturstein-Monitoring: Nachkontrolle und Wartung als zukunftsweisende Erhaltungsstrategien. Fraunhofer IRB Verlag Stuttgart

(The most important facts and results for all investigated objects are summarised on the project homepage www.naturstein-monitoring.de)

Calkarow program, version 3.2: Copyright by Dr. E. Wendler and Prof. Dr. S. Pfefferkorn

DIN EN 1062-1 Beschichtungsstoffe - Beschichtungsstoffe und Beschichtungssysteme für mineralische

Grimm W.-D. 1990: Bildatlas wichtiger Denkmalgesteine der Bundesrepublik Deutschland, München

ICOMOS-ISCS International Council on Monuments and Sites 2010. Illustrated glossary on stone deterioration patterns. Int. Scientific Committee for Stone, Paris 2010

Meinhardt-Degen J. & Snethlage R. 2004: Durability of hydrophobic treatment of sandstone facades – Investigations of the necessity and effects of re-treatment. In: Kwiatkowski, D. & Löfvendahl (eds.): Proc. 10th International Congress on Deterioration and Conservation of Stone, Vol. 1, Stockholm, S. 347-354.

Niemeyer, R. 2010. Evaluation algorithm of Niemeyer: Copyright by Dipl. Chem. R. Niemeyer, Niedersächsisches Landesamt für Denkmalpflege

Snethlage R. 2008: Leitfaden Steinkonservierung. Fraunhofer IRB Verlag Stuttgart

Snethlage R. 2011: Stone conservation. In: S. Siegesmund and R. Snethlage (eds.): Stone in Architecture, IVth ed. Chapter 7, 411-544. Springer Verlag Heidelberg

Snethlage R. & Wendler E. 1988: Durability of hydrophobing treatments of natural stone buildings, Proc. Intern. Symp. Geol. Soc., 19.-23. Sept. 1988, Athens, S. 945-952.

Snethlage R. & Wendler E. 1996: Methoden der Steinkonservierung – Anforderungen und Bewertungs-kriterien, In: Snethlage, R. (eds.): Denkmalpflege und Naturwissenschaft, Natursteinkonservierung I, Verlag Ernst & Sohn GmbH, Berlin, S. 3-40.

Substrate und Beton im Außenbereich - Teil 1, 2004-2008

VDI Richtlinie 3798, Blatt 3 (1998): Untersuchung und Behandlung von immissionsgeschädigten Werkstoffen, insbesondere bei kulturhistorischen Objekten - Blatt 3: Die graphische Dokumentation. Verein Deutscher Ingenieure, Düsseldorf

WTA data sheet E 3-17 (2010): Hydrophobierende Imprägnierung von mineralischen Baustoffen. Wissenschaftlich-Technische Arbeitsgemeinschaft für Bauwerkserhaltung und Denkmalpflege e.V., München