WEATHERING CHARACTERISTICS OF STONE CULTURE HERITAGE 
ON THE BASIS OF THE CLIMATE CONDITION IN KOREA

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Abstract
We carried out statistical analysis on the status of exfoliation on 533 stone culture heritage sites designated as national treasures and the climate condition data for the period 1971 to 2010 to verify weathering characteristics of the stone according to the climate conditions in Korea. The results indicated a high exfoliation rate of 70.1%. Based on the statistical research of climate condition, the exfoliation rate of Korean stone cultural heritages is 85.6% in the decomposition region with frost action, 78.0% in the strong decomposition region and 55.3% in the moderate decomposition region. Therefore, the surface weathering occurring in Korean stone cultural heritages is assumed to be caused by repeated freezing and thawing and physicochemical weathering from precipitation.

Keywords: weathering, exfoliation, climate, GIS, frost action

1. Introduction
Korean cultural heritages are classified into several categories: national treasures, treasures, natural monuments, municipal and provincial cultural heritages and so on. Stone cultural heritages are 29.2% among designated cultural heritages. In addition, in the category of structural cultural heritages, 76.2% of National Treasures, 41.7% of Treasures, 84.5% of municipal and provincial cultural heritages are made of stone. Many of these remain sound thanks to their great endurance compared with other heritages or other materials.

Even though the endurance of stone is higher than that of other materials, Korean stone cultural heritages have been weathered by freezing and thawing, chemical weathering, salt crystallization, biological weathering and so forth, being exposed for long periods from hundreds to thousands of years. This caused damage by cracks, exfoliation, surface change, etc. Exfoliation is regarded as the most fatal factor in the damage, considering the properties of the cultural heritages on which various patterns were carved.

Scientific conservation researches are needed to inspect the damage based on the properties of the component rocks in order to establish a conservation program. Many such researches have been conducted and the quality has been raised (Lee et al. 2003, 2005, 2006; Lee and Yi 2007; Fitzner et al. 2004; Dwivedi et al. 2008).

However, the researches on the weathering process of Korean stone cultural heritages have never been conducted. The influential factors for the weathering of stone cultural heritages are climate conditions, shape of cultural heritages, environment, time,
terrain, vegetation and so on. The climate conditions are the most influential factor on weathering.

To preserve stone cultural heritages, the weathering properties have to be revealed based on the climate conditions. This study, therefore, statistically analyzed the exfoliation and climate conditions of 515 cultural heritages, which were designated as Treasures and National Treasures during the period from 1971 until 2010.

2. Method of study

The study of rock weathering has to check the properties of physicochemical changes that have occurred from the initial unweathered rock. There are, however, time constraints in the study since the natural weathering progresses very slowly. Hence, researchers have conducted studies of the changes in the properties of the main component rocks by weathering, through an artificial weathering experiment, which is conducted in a set environment (Goudie 1993; Rossi-Manaresi 1991). In these studies, however, there are limitations in considering every factor involved in weathering in the natural environment where various factors influence in the weathering process.

The surfaces of stone cultural heritages were initially fresh. As time passed, however, the surface of stone started to be damaged. Therefore, the mechanism of weathering in natural environments can be revealed by analyzing the correlation of weathering degree of the present state and the factors in weathering environment.

This current study conducted a statistical analysis on the status of exfoliation in 515 Treasures and National Treasures, and the natural factors involved in surface weathering are studied by analyzing the result of the statistical analysis considering Korean terrain and climate conditions.

Korean National Research Institute of Cultural Heritage had researched the weathering degree of Treasures and National Treasures from 2001 until 2005. Based on the result of the research, a statistical analysis on the status of their exfoliation was conducted classifying them according to the criteria; rock classification, weathering degree, time and area.

Climate conditions vary according to the area and terrain. In order to observe the climate conditions in the Korean peninsula terrain, the correlation of Korean mountain ranges mapped in GIS and weather data collected in each area was revealed by synthesizing the data. Furthermore, the correlation diagram of climate conditions and weathering, which was designed by Fookes et al. (1971) was applied to the classification of decomposition regions in Korea.

On the basis of this diagram, the properties of weathering according to climate conditions are revealed by statistically analyzing the exfoliation of stone cultural heritages.

3. Result and Discussion

3.1. Status of exfoliation

The Korean National Research Institute of Cultural Heritage had researched the degree of weathering of Treasures and National Treasures from 2001 until 2005. According to the statistical analysis results, an exfoliation rate of 70.1% was noted for National Treasures. A statistical analysis was conducted to specifically observe the
status of exfoliation, classifying the cultural heritages according to rock classification, weathering degree, age and area (Table 1).

The status of exfoliation was statistically analyzed by classifying them into igneous rock, sedimentary rock and metamorphic rock according to the environment in which each rock had formed. The result shows that the exfoliation rate is 67.3% in igneous rock, 80.0% in sedimentary rock and 86.3% in metamorphic rock. Therefore, it is concluded that sedimentary rock and metamorphic rock, which have properties of stratification and schistosity are more susceptible to exfoliation than igneous rock which has massive structure.

In the case of exfoliation classified by degree of weathering, 4 out of 10 stone cultural heritages, which were previously graded as fresh, recorded a 40% exfoliation rate. 65.4% was recorded in the slightly weathered degree, 69.1% in the moderately weathered degree, 72.1% in the highly weathered degree and 84.1% in the completely weathered degree. These results indicate that the exfoliation occurs more aggressively in heritages of higher weathering degree.

In addition, in stone cultural heritages in which granite is the main component (73%), exfoliation rate was 37.5% in the fresh degree, 66.1% in the slightly weathered degree, 62.8% in the moderately weathered degree, 66.7% in the highly weathered degree and 80.6% in the completely weathered degree. Therefore, in granite, the exfoliation rate increased as the weathering degree increased.

A statistical analysis was conducted to observe the correlation of exfoliation and time. As a result, exfoliation occurred in both stone cultural heritages of the Bronze Age. In the stone cultural heritages of the Three Kingdoms period (before 7C), exfoliation occurred in 35 of the 46 recording heritages (76.1%). Exfoliation occurred in 157 of 207 (75.8%) stone cultural heritages of the Goryeo Dynasty (7C-10C). Exfoliation occurred in 27 of 39 (69.2%) stone cultural heritages of the Joseon Dynasty (14C-19C), which revealed that the exfoliation rate is proportionate to the age of the cultural heritages. Nevertheless, the exfoliation rate in the stone cultural heritages of the United Silla (7C-10C) was the lowest with the result of exfoliation occurred in 139 heritages among 216 heritages.

Furthermore, the status of exfoliation in the stone cultural heritages of each time period that were composed of granite, the exfoliation rate was 73.5% during the Three Kingdoms period, 60.5% during the United Silla, 70.9% during Goryeo Dynasty and 60.0% during the Joseon Dynasty, which shows that the rate in the United Silla was nearly the lowest. Considering the tendency that the rate was lower in the later time except for in the United Silla, other factors may be involved that influence the rate of exfoliation.

In the status of exfoliation according to the area, exfoliation occurred in all 41 stone cultural heritages in northeast area and 35 of 59 (59.3%) in northwest area. Exfoliation occurred in 133 of 216 (61.6%) in the southeast area, 78 of 112 (69.6%) in the southwest area and 74 of 86 (86.0%) in the midwest area.

The analyses of those composed of granite according to the area, exfoliation rate was 100% in northeast area, 55.1% in northwest area, 52.1% in southeast area, 62.3% in southwest area 62.3% and 85.7% in midwest area, which shows a similar rate in northeast and midwest area, but the rate was 13-45% lower in northwest, southeast and
southwest area than the others. The results show the distinct difference in exfoliation rate of each area. It is assumed that the rate depends on the features of each area.

#### Table 1. The status of exfoliation in the stone cultural heritages in Korea

<table>
<thead>
<tr>
<th>Classification</th>
<th>All of the stone cultural heritages</th>
<th>Heritage composed of granite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Treasu rate</td>
<td>Exfoliation rate(%)</td>
</tr>
<tr>
<td>Fresh</td>
<td>10</td>
<td>4 40.0</td>
</tr>
<tr>
<td>Slightly weathered</td>
<td>81</td>
<td>53 65.4</td>
</tr>
<tr>
<td>Moderately weathered</td>
<td>233</td>
<td>161 69.1</td>
</tr>
<tr>
<td>Highly weathered</td>
<td>147</td>
<td>106 72.1</td>
</tr>
<tr>
<td>Completely weathered</td>
<td>44</td>
<td>37 84.1</td>
</tr>
<tr>
<td>Total</td>
<td>515</td>
<td>361 70.1</td>
</tr>
</tbody>
</table>

#### 3.2. Terrain and climate conditions

According to the result of the statistical analyses of exfoliation and surface change the rate of surface change has the largest deviation in the analysis conducted according to the area. It is estimated that the result was caused from the different physical and chemical environment of weathering in each area. Hence, the data on domestic terrain and weather are synthesized to observe the properties of climate conditions in each area.
Korean terrain features mountain areas and mountain ranges taking 66% area of the land. Korean Research Institute For Human Settlements redefined the features of mountain ranges in Korean Peninsula by utilizing the space analysis method (GIS) (Kim et al. 2004). The writer classified the mountain ranges in Korean Peninsula into three categories; the main mountain ranges which are the highest and longest as the first mountain ranges, the second and third mountain ranges considering the link with the first mountain ranges. Several mountain ranges which have no link with the first, second and third mountain ranges were classified as individual mountain ranges (Figure 1A).

![Figure 1. The interrelation of terrain and climate conditions in Korea. (A) Mountain ranges in Korea (modified Kim et al. 2004), (B) The interrelation of mountain ranges and annual mean temperature in Korea, (C) The interrelation of mountain ranges and annual mean precipitation in Korea.](image)

Since Korea is geographically located in the east coast of the Asian continent and middle latitude, the annual variation of temperature is large and it has four distinct seasons; spring, summer, fall and winter. The four seasons are created because the Korean peninsula is influenced by different air masses in each season; the warm and dry Yangtze River air mass in spring and fall, the heated and wet North Pacific air mass in summer and the cold and dry Siberia air mass in winter. Korea has a unique climate, which has different temperature, precipitation and air mass in each season.

Korean annual mean temperature is 12.6°C and annual precipitation is 1388 mm. The deviation of annual mean temperature and precipitation, however, varies in each area, which shows the close relationship with mountain ranges. The annual mean temperature is under 12°C in northwest of the first mountain ranges and over 12°C in the southeast. In addition, annual mean temperature varies in each area classified by the first, second, third and individual mountain ranges (Figure 1B).

Researching annual mean temperatures in each season, the annual mean
temperature of the coldest month (January) is -1.4°C. The annual mean temperature in southeast area is around 3°C, and for the northeast area, which is located in the mountains is around -7.6°C. Annual precipitation also varies in each area influenced by the mountain ranges. It is 1100–1400 mm in the direction of northwest of the first mountain ranges and 1000-1200 mm in the direction southeast of the first mountain ranges. Furthermore, the annual precipitation is 1800 mm in the southernmost coast area and northeast mountain area where the first and second mountain ranges meet (Figure 1C).

3.3. Interpretation of the correlation of climate conditions and exfoliation

Influential factors of the weathering of stone cultural heritages are their geometry, conservation environment, climate conditions, time, terrain, vegetation with climate conditions being the most influential factor on weathering. As a result of the statistical analysis of synthesized weather data from each area, climate conditions vary according to terrain of the area.

Precipitation and temperature are the most important factors in climate conditions, and the correlation of the two factors determines the weathering process and its outcome. In the two factors, precipitation has more influence on weathering. This is because water is involved in the biochemical process as well as the physicochemical weathering process.

Based on the above observation, in order to reveal the influence of Korean climate conditions on stone cultural heritages, this study applied the correlation diagram of climate conditions and weathering designed by Fookes et al. (1971) to the mean temperature and precipitation data collected for 40 years (1971-2010). As a result, the decomposition region is classified into strong decomposition region, moderate decomposition region and moderate decomposition region with frost action (Figure 2).

In order to observe the distribution of the Korean decomposition regions, GIS was used to collect the data of latitude and longitude of the weather observation area. The data collected in each climate observation area and decomposition region were synthesized and 2D modeling of the data was made to show the distribution of decomposition regions.
Figure 2. Correlation diagram of climate conditions and weathering in Korea (modified Fookes et al. 1971).

Figure 3. 2D modeling for correlation diagram of climate conditions and weathering in Korea.

Table 2. The exfoliation rate according to the decomposition region in Korea.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Treasure</th>
<th>Exfoliation</th>
<th>Rate(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong decomposition area</td>
<td>109</td>
<td>85</td>
<td>78.0</td>
</tr>
<tr>
<td>Moderate decomposition with frost area</td>
<td>97</td>
<td>83</td>
<td>85.6</td>
</tr>
<tr>
<td>Moderate decomposition area</td>
<td>246</td>
<td>136</td>
<td>55.3</td>
</tr>
<tr>
<td>Total</td>
<td>452</td>
<td>304</td>
<td>67.3</td>
</tr>
</tbody>
</table>
As a result, it was confirmed that decomposition regions vary according to their climate conditions. Part of the west area and south coast area are in the strong decomposition region and the northeast area is in the moderate decomposition region with frost action. On the other hand, the southeast area, where the stone cultural heritages of the United Silla are distributed, is in the moderate decomposition region (Figure 3).

In addition, the 452 stone cultural heritages composed of igneous rock are classified into cultural heritages with exfoliation and those without exfoliation, and they are described in the 2D modeling. The cultural heritages with exfoliation are shown in the strong decomposition region and decomposition region with frost action. On the contrary, those without exfoliation are shown in the moderate decomposition region.

Studying the exfoliation rate according to the decomposition region, 85 heritages among 109 stone cultural heritages in the strong decomposition region have exfoliation (78.0%), and it was 85.6% (relatively high) in the moderate decomposition region with frost action. It was, however, 55.3% (relatively low) in the moderate decomposition region, showing exfoliation in 136 heritages in 246 stone cultural heritages (Table 2).

According to the result of the statistical analysis of exfoliation in stone cultural heritages regarded as Treasures and National Treasures, the exfoliation rate of stone cultural heritages of the United Silla (7C-10C) is about 5-9% lower than that of the Goryeo Dynasty (10C-14C) and the Joseon Dynasty (14C-19C). This is because the stone cultural heritages of the United Silla concentrated in southeast area are influenced by weathering less than other heritages thanks to its location in the moderate decomposition region.

Based on the above results, it is concluded that the degree of surface damage occurring in stone cultural heritages depends on the climate conditions and that physicochemical weathering and repeated freezing and thawing caused by high temperature and a great amount of precipitation are the main factors in weathering. Thus, different properties of weathering in each area have to be considered in the conservation of stone cultural heritages.

Furthermore, properties of weathering are changing according to the change of mean temperature and precipitation influenced by global warming. Figure 4 shows the correlation of climate conditions and weathering by calculating the average degree of mean temperature and precipitation from 1971 to 2010, which describes the change of areas from decomposition region with frost action to strong decomposition region after moderate decomposition region and the change from moderate decomposition region to strong decomposition region. Therefore, a long-term conservation strategy is required to be prepared by estimating the weathering change according to changes in climate conditions.
4. Conclusions

The decomposition regions influenced by Korean climate conditions are classified into strong decomposition region, moderate decomposition region and moderate decomposition region with frost action. The exfoliation rate of Korean stone cultural heritages is 85.6% in the decomposition region with frost action, 78.0% in the strong decomposition region and 55.3% in the moderate decomposition region. Therefore, the surface weathering occurring in Korean stone cultural heritages is assumed to be caused by repeated freezing and thawing, physicochemical weathering from significant precipitation.

References


