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Investigation of Environmental Factors Influencing the Deterioration of Nikka Stone in Koshien Hall

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Abstract: Environmental factors influencing the deterioration of Nikka Stone used in Koshien Hall were investigated through field surveys of current conditions. The main results obtained were as follows:
1. Deterioration of Nikka Stone used in Koshien Hall was classified into three categories: algal contamination, detachment, and salt efflorescence.
2. There are several possible causes of detachment, including freezing/thawing cycles caused by high stone-water content and high concentration of evaporation from the surface of water from the surroundings, salt efflorescence, and so on.
3. Small quantities of rainfall and sunshine can contribute to algal growth.

1. Introduction

Koshien Hall (formerly Koshien Hotel), built more than 80 years ago, is listed as a Heritage of Industrial Modernization site and Important Cultural Properties. It is used as the campus of the Department of Architecture of Mukogawa Women's University. One of the characteristics of Koshien Hall is that a tuff, referred to as Nikka Stone, was used on the exterior of the building. It is said that architect Arata Endo used Nikka Stone to decorate the exterior and interior because it is soft and easy to carve (Miyake, 2009).

Koshien Hall has been renovated several times and the Nikka Stone has also been replaced and repaired[1]. However, much of this stone has deteriorated, especially on the exterior. Although the stone has undergone marked deterioration and has been replaced with a new stone, it is becoming difficult to obtain a new stone given that many Nikka Stone quarries have ceased to operate. Existing materials must therefore be maintained in use for many years, instead of being replaced.

There are generally several factors contributing to stone deterioration, such as rainwater, solar radiation, and temperature variation (ex. Ogura et.al., 2011, Miyauchi et.al., 2008, and Nakamura et.al., 2008). In order to maintain existing materials in use for extended periods, it is important to minimize the

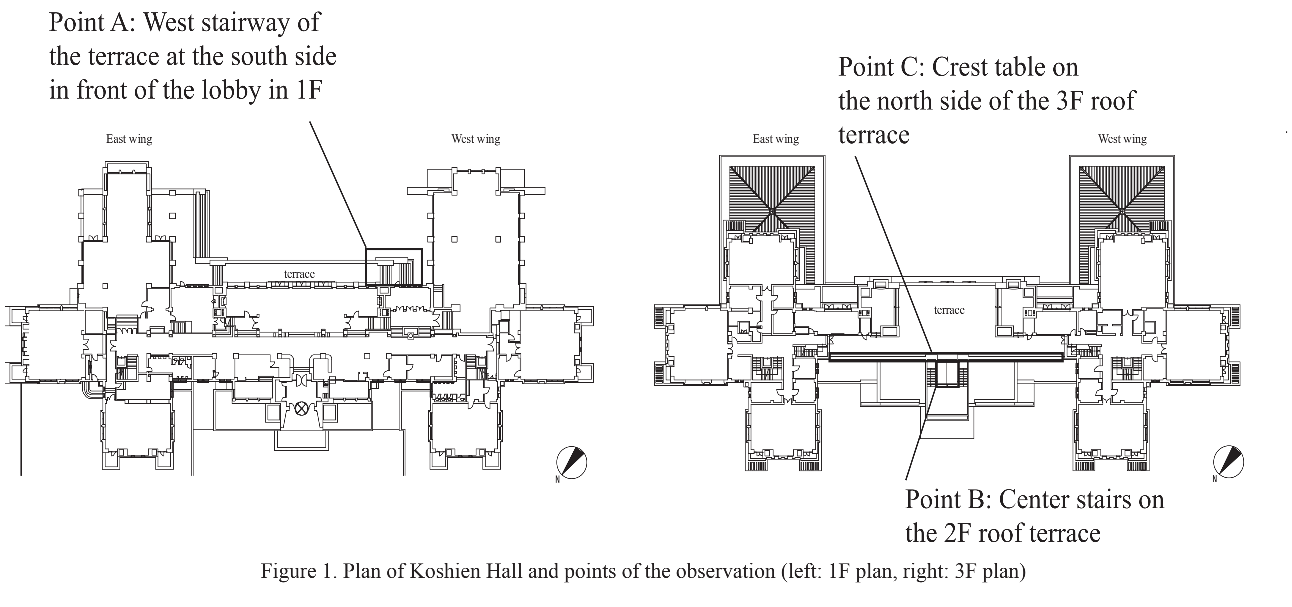


Figure 1. Plan of Koshien Hall and points of the observation (left: 1F plan, right: 3F plan)

influence of deterioration factors.

In order to prolong the lifetime of Nikka Stone, this study quantitatively and qualitatively describes the environmental factors contributing to deterioration of Nikka Stone, proposing a strategy for its conservation. In the first stage of this study, the current condition of Nikka Stone was investigated. Special attention was paid to quantitative analysis of the impacts of water content, reflected solar radiation, and nocturnal radiation. The ultimate goal of this study is to contribute to the establishment of a conservation and maintenance program using traditional architecture.

2. Characteristics of Nikka Stone

2.1. GENERAL CHARACTERISTICS

The Nikka Stone used in Koshien Hall was produced in Kanagaso-machi, Komatsu (Ishikawa Prefecture). Nikka Stone is a volcanic tuff, which has lower specific gravity, higher water absorption, and lower compressive strength than granite and andesite (Kishitani, 1987). The tuff is also characterized by high burning resistance and low heat conductance. Compared to Oya Stone (another tuff), Nikka Stone is dense and has high burning resistance (Yoshioka et. al., 1982).

2.2. WATER CONTENT

Most stone deterioration is caused by the presence of water (Figure 2) and materials with high water absorption capacities tend to maintain water to a greater degree. Water-related characteristics are thus important factors in this study.

The maximum water content of the Nikka Stone used in Koshien Hall was measured and the process of water absorption was observed [2]. Results indicate that water on the surface of the stone moves quickly while water inside the stone moves slowly. Water content saturated at around 23%.

3. Current Condition of Nikka Stone

3.1. RELATIONSHIP BETWEEN ENVIRONMENTAL FACTORS AND TYPE OF STONE DETERIORATION

Phenomena affecting Nikka Stone at present include detachment, flaking, powdering, and cracking caused by the decay of components; these lead to changes, such as hardening of the stones (Nakamura et. al., 2012 and Young et. al., 2004). There are also several types of detachment caused by changes in stone water content, by high or low temperatures and humidity conditions, and by stone freezing and thawing due to changes in surrounding environmental conditions. Scaling or salt efflorescence on the stone surface represents another type of deterioration. This leads to other features of stone decay, such as powdering. These phenomena are caused by existing source material and cycling of wetting and drying conditions.

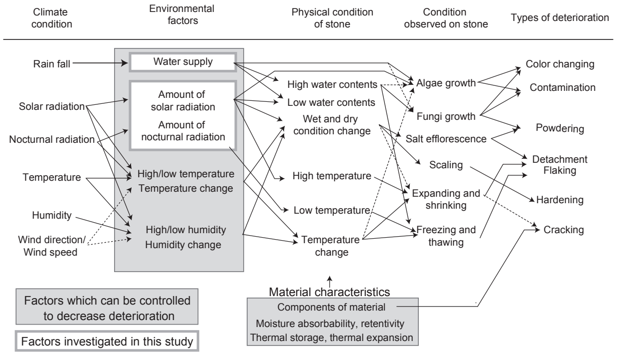


Figure 2. Relationship between environmental factors and type of stone deterioration

Biological deterioration is also considered in this study. Flaking, powdering, pitting, and stone color changes are known to be caused by bacterial or fungal growth (Caneva et. al. (ed.), 2009). Algae and lichen lead to surface contamination and encrustations, contributing to a change in image from that conceived of by architects. In addition, growth of moss and higher plants causes physical damage to stones. Biological growth occurs under conditions of minimal light and with the persistence of moisture.

This chapter reports observation results of deterioration conditions of Nikka Stone in Koshien Hall. Chapter 4 reports on measurement of solar radiation, nocturnal radiation, and rainfall (the environmental factors shown in Figure 2) and the consequent moisture conditions of stones; the relationship between environmental factors and type of stone deterioration is examined in Chapter 5.

3.2. TYPES OF DETERIORATION

In order to understand the relationship between stone deterioration and environmental factors, the current degree of deterioration of Nikka Stone was investigated visually and classified into several types (Table 1). Additionally, current environmental conditions causing deterioration were investigated. The typical deterioration observed at points A (the west stairway of the terrace at the south side in front of the lobby in 1F), B (the center stairs on the 2F roof terrace), and C (the crest table on the north side of the 3F roof terrace) in Figure 1 were analyzed in detail in section 3.3.

After investigating the entire building, deterioration was classified into three types: algal contamination, detachment, and salt efflorescence (Table 1).

(1) Algal contamination

Marked algal growth was observed on the floor stones on the surrounding of West Hall (Figure 3a). Here, most of the Nikka Stone was covered by moss. The ends of the eaves on the west side exterior wall of the West Wing and east side exterior wall of the East Wing were darkened by algae, while the crest tables of the barony wall under the eaves were not darkened (Figure 3b). There are a number of water trace lines caused by algae and dust on the eaves on each south side (Figure 3c).

The results of the environmental survey indicate algal contamination in shadowed areas without direct solar radiation and in places where water persists for long periods of time.

(2) Detachment

Several types of detachment were observed. Large detachment tends to occur on horizontal surfaces, such as the stairs of the 2F roof terrace (point B, Table 1) and the crest table on the north side of the 3F roof terrace (point C, Table 1). Fine detachment, such as flaking, was observed on the surface of the outside floor on the east and west sides of the West Hall (Figure 3a), on the exterior steps at the front entrance, on the stairway of the terrace at the south side in front of the lobby in 1F (point A, Table 1 and Figure 3d), and in other locations. Algae were not observed on these flaking areas. Detachment with salt efflorescence was observed on the lower side of the pillars on the south side terrace of the 1F lobby (Figure 3a) and in other locations.

Several factors are thought to cause detachment, such as freezing and thawing, salt efflorescence, and others.

(3) Salt efflorescence

Salt efflorescence appeared in small limited areas, such as on the lower parts of pillars on the south terrace of 1F (Figure 3e) and on baseboards under the entrance doors of 3F (Figure 3f). The causes of salt efflorescence include repeated cycling of dry and wet conditions, i.e., changes in moisture content of materials and temperature changes in the presence of salt.

3.3. DETAILS OF DETERIORATION AT POINTS A, B, AND C

In order to quantify deterioration and contributing environmental factors, detailed investigations (including measurement of sky view factors, water content, and observation of surface conditions of Nikka Stone) were carried out at points A, B, and C (shown in Figure 1). These results are shown in Figure 4.

(1) Point A

Fine detachment flaking was observed only on the north side of the upper stairs (Figure 3d, Figure 4: the inner side of the dotted line at area I of point A). The flaking area comprised approximately 1/3 of total area. Other areas were in good condition. Water repellent materials had been applied to the surface of the Nikka Stone here in 2009 [1]. Even now, water films are observed during rain; the effect of the water repellent thus remains. Visual observations confirmed that there is no salt efflorescence.

(2) Point B

Steps: Algal contamination and detachment of several sizes were observed. Nikka Stone was significantly darkened by thick algal growth (Figure 3g). Compared to the top stairs in area I of point B in Figure 4, there was much more algal growth on the second, third, and lower stairs. In addition, large detachment was observed in area II; one instance was about 15 cm wide and more than 5 mm thick.

Crest table: Algal contamination and detachment were observed. Algal growth was less extensive than on the steps. There were several instances of small detachment compared to the steps, some of which had been repaired with mortar. The crest tables of III and III' in Figure 4 were replaced with new materials in 2013 because of serious deterioration.

(3) Point C

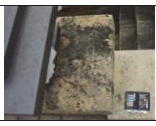
Algal contamination was observed. This was extensive in the area near the west and east buildings and was less extensive at the center. Although detachment is now rarely observed, many spots had been repaired with mortar and resin. Algal growth was observed in the chinks between the original stone and mortar.

4. Detailed Investigation of Environmental Factors Influencing Deterioration

Environmental observations were carried out at places where typical deterioration was observed during the preliminary investigation (shown in Figures 1 and 4, points A, B, and C). The main types of deterioration observed at these points were detachment and algal contamination.

The relationship between environmental factors and deterioration is shown in Figure 2. The environmental factors

Table 1. Current state of deterioration in Koshien Hall

Type of deterioration	Condition	Features of the place where deterioration was observed.	Notes
Algal contamination		Places where rain water drips. For example, the end of the eaves in both wings, the east side wall of the west wing, steps and crest table in the roof terrace.	- Algal contamination was observed in places where rain drip was significant. - Abundant algal growth was seen in places shaded from direct solar radiation by other buildings and trees.
Detachment		Exterior wall at the front entrance, steps on the south side terrace of the West Hall, lower side of the pillars on the south side terrace of the 1F lobby, steps of roof terrace in 2F, etc.	- There are several types of detachments depending on the area. - Compared with contamination of algae, areas of detachments are limited. - Salts efflorescence was observed on the lower part of the pillars on the south terrace in front of the West Hall at the same time.
Salt efflorescence		Lower part of pillars on the south terrace of 1F, baseboards in the 2F roof terrace, baseboards under the entrance doors of 3F, etc.	The salts were identified as sodium sulfate, which causes serious deterioration of porous materials. Salt efflorescence was observed where water penetrates easily.

a b c d e f g

a) Algal contamination and detachment at the floor stone, b) Algal growth in the west side of West Hall, c) darken trace of the eaves, d) flaking on the stairway of the terrace at the south side in front of the lobby in 1F, e) detachment with salt efflorescence on the lower side of the pillars, f) salt efflorescence on the baseboards under the entrance doors, g) detachment and algal growth at the center stairs on the 2F roof terrace, point B.

Figure 3. Deterioration conditions

leading to algal contamination are thought to be high water supply and resulting high water content of materials, lack of dry conditions, and solar radiation for plant photosynthesis. However, large quantities of solar radiation in fact prevent algal growth. Detachment can be caused by freezing and thawing of water contained in materials, expansion and shrinkage of materials, and salt efflorescence, among other factors. All of these are affected by the presence of water, temperature conditions, wetting and drying cycles, and other such influences.

In order to elucidate the relationship between the effect of these environmental factors and deterioration, sky view factors and material water content before and after rain were observed.

Sky view factors, calculated from fish eye photos (Futagami and Uno, 2011), show the ratio of the sky area that is not shadowed by surrounding buildings, trees, or other features to the whole sky. Using these factors, we can quantitatively calculate the influence of solar radiation (especially diffused solar radiation) and of nocturnal radiation that leads to a decrease in stone temperature. High sky view factors equate to high influence of both solar radiation and nocturnal radiation. In addition, the influence of direct solar radiation was accounted for in the sky view photos.

The water content of stone is a consequence of environmental conditions, such as water supply, amount of solar radiation, temperature changes. The presence of water causes contamination by biological growth, detachment by freezing and thawing, and salt efflorescence.

Freezing and thawing occur easily under conditions of low stone temperature resulting from low air temperature and high nocturnal radiation. The same measurements as for observation of algal growth were therefore conducted, and sky view factors and material water content before and after rain were observed. In addition, the total days when freezing could occur were counted.

4.1. CLIMATE OF NISHINOMIYA CITY

Nishinomiya city is located in a warm-temperature region. Table 2 shows the number of days when outdoor temperature was lower than 0°C and 4°C, respectively in Nishinomiya city. When considering nocturnal radiation, freezing and thawing can occur when air temperature is higher than 0°C, because surface temperature becomes lower than air temperature. Maximum nocturnal radiation is about 93W when the whole sky was clear (without clouds) (Hokoi et. al., 2002), leading to surface temperature decreases at 4°C. When there is large nocturnal radiation under clear sky conditions, even if the outdoor air temperature is 0–4 °C, the surface temperature can be below 0°C.

Table 2. Number of days below 0 and 4°C in Nishinomiya city

Year	0°C	4°C
Dec. 2004-March 2005	8	60
Dec. 2005-March 2006	11	80
Dec. 2006-March 2007	0	51
Dec. 2007-March 2008	4	59
Dec. 2008-March 2009	1	51
Dec. 2009-March 2010	4	53
Dec. 2010-March 2011	8	76
Dec. 2011-March 2012	1	71
Dec. 2012-March 2013	9	77
Dec. 2013-March 2014	3	61

* The data obtained the website in Japan Meteorological Agency.

According to meteorological data for the last decade, the number of days when temperature was lower than 0°C (Table 2) was 4.9 days per year on average, with 63.9 days when the temperature was lower than 4°C. It is therefore clear that there is high potential for freezing and thawing of materials.

4.2. INFLUENCE OF ENVIRONMENTAL FACTORS

4.2.1. Nocturnal radiation, solar radiation, and rain

In order to quantify the influence of nocturnal radiation and solar radiation, sky view factors were measured at three points. Figure 5 shows the ratio of sky view factors. The following are sky view factor conditions at each point.

(1) Point A

Sky view factors were low (between 10–17 %) and part of the zenith was covered by an eave. Rain therefore rarely fell on the steps and there was less solar and nocturnal radiation.

(2) Point B

The sky view factor was high (between 42–69 %). Rainfall, solar radiation, and nocturnal radiation were therefore high.

(3) Point C

The sky view factor was high (between 72–74 % at the center and between 26–36 % at the west and east sides). A lot of rain therefore fell here, and solar radiation and nocturnal radiation were high. Closer to the sides of the west and east buildings, the sky view factor was lower because of the presence of a large tree on the north side of the west part of the building.

4.2.2. Water content of materials

The measurement of material water content was carried out after 12 sunny days without rain (for dry stone conditions), and after rain (for wet stone conditions) [2]. Figure 6 shows the results obtained. The contrasting color density shows the degree of water content. From the results, the following observations are clear:

(1) Point A

Water content was low (around 8–15 % before rain and around 10–18 % after rain) everywhere; in particular, the water content of places under eaves was relatively lower, even after rain.

(2) Point B

The water content was around 15–18 % (before rain) and 15–21 % (after rain) at the top stair, while that of steps below the second step was 15–30 % (before rain) and 19–32 % (after rain). The water content of the lower side is obviously high, and in area II was over 23% (saturated conditions). These points were thus wet all the time.

(3) Point C

Water content was low everywhere, at 2–12 % before rain and 3–14 % after rain. It should be noted that, even when there was significant rain, this location dried out quickly.

4.2.3. Observation of drying process after rain

In order to consider the relationship between degree of deterioration and environmental factors, especially related to water, the drying process was investigated after rain (Figure 6).

(1) Point A

Only places under the eaves do not receive much rain and their water content was slightly lower than that in other areas.

(2) Point B

Steps: The areas of color change induced by water increased a few days after rain at the lower part of the steps. On the third step from the bottom, the area of color change induced by water did not disappear by ten days after a rain event.

Crest tables: The stones were moist, but no holes with water or wet stains were observed.

(3) Point C

There were several gullies with little water. However, color change of the stone surface could not be clearly distinguished because of algal contamination.

5. Relationship between Current Deterioration and Environment

(1) Point A

Fine detachment, such as flaking, was observed on the north side of the upper stairs. There was no salt efflorescence noted via visual observation.

Areas with detachment damage at area I in point A in Figure 4 were shadowed from rain. It is therefore thought that the water supply from the surface is small and that water may originate from neighboring rain-exposed stones. Although these areas have low sky view factors compared to other areas of B or C, the south side is open and the area is influenced by direct solar radiation at noon. When there is a water source, which should be from the back side of the stone, constant evaporation from the surface of the stone under the eave should occur. Additionally, water repellent would prevent evaporation from the surface, while evaporation would be concentrated and would continue in deteriorated areas without water repellent.

Factors contributing to detachment damage at point A should therefore be increasing temperature, drying caused by solar radiation, concentrating evaporation on the surface along with water supplied from nearby stones, and wetting/drying cycles. The effect of water repellent on salt efflorescence requires more detailed investigation and experimentation.

(2) Point B

Steps: Detachment and algal contamination were mainly observed. Water content was high and area II in Figure 6 was always wet. Because wetness appears and spreads a few days after a rain event and continues for several days, water supply is too excessive to be explained by rainfall onto the surface. Since there are wide 3F roof terraces without roofs on the upper side of point B, the rain water falling to the 3F terrace can seep through the mortar joints to the lower steps. After the surface of the terrace has dried, water might remain under the tiled floor of the 3F roof terrace and flow to the back side of the stone on the steps. This may be the source of water leading to the high water content of the steps. Water supply is substantial and persists for days.

Because of this constant water supply and high sky view factors, freezing and thawing occur and damage the stone. However the high heat capacity of Nikka Stone that absorbs solar radiation during daytime works to maintain heat and can buffer the decrease in surface temperature. These effects should be carefully simulated. High water content also causes substantial algal growth. It is therefore better if water supply is decreased.

Crest tables: Detachment (of several sizes) within the stones, which are filled with mortar, are the main causes of deterioration. This area has high sky view factors and slightly low water content. Slightly high water content was measured after rain only on the north side of the crest table stone in III and III'.

Except at the two latter locations, some halls have been filled with mortar, which tends to have low water penetration and low water content. Although rainfall on the stone is high, it drains immediately afterwards and the upper portions dry out (except in III and III'). In order to prevent algal contamination, use of water repellent can therefore be effective. However, some water remains on the surface in the small hall, and water content can be high, causing freezing and thawing damage; the surface should therefore be smoothed with a material like mortar or resin.

Because III and III' stones are laid at a lower position than other stones, rainwater flows on to them and persists for a long period of time. In addition, in parts of III and III' that were replaced with new material last year, the stone surface is not covered by mortar or resin and water can easily penetrate. These parts receive substantial water from the upper side, so waterproofing should be applied to the surface and to the back part. There is currently no detachment; however, there is a high possibility of deterioration caused by freezing-thawing occurring in future.

(3) Point C

Algal contamination and detachment were mainly observed. Because the condition of the central area is the same as in upper areas of point B with high sky view factors and low water content, freezing and thawing may be the main cause of deterioration.

Algal contamination is significant near the building, especially on the west side, because of the presence of a large tree on the north side. It is thought that algal growth is influenced by both rain and by limited solar radiation. To counter this, in addition to a surface repellent, controlling tree growth to adjust solar radiation can be effective at reducing algal growth.

This location could be influenced by repeated drying and wetting cycles. Water content on the west side was slightly higher than on the east side, because there are large trees on the north side.

6. Conclusion

In this paper, the influence of environmental factors on the deterioration of Nikka Stone in Koshien Hall was investigated and three areas where typical deterioration was observed were investigated in detail. The main results are as follows:

1) Deterioration of Nikka Stone was classified into three types: algal contamination, detachment, and salt efflorescence.

2) The cause of detachment on the west stairway of the terrace at the south side in front of the lobby in 1F was presumed to be the concentration of evaporation on the surface, with water supply from surrounding stones that have been wet by rain.

3) Deterioration on the steps of the central stairs on 2F roof terrace was due to algal contamination and freezing-thawing caused by continual wet conditions. From circumstantial evidence, the water can be presumed to have been supplied from the back side terrace. The management of water supply from this area in 3F should therefore be considered.

4) The deterioration of the crest tables on the 3F roof terrace was due to algal contamination and detachment. Detachment can be caused by freezing and thawing influenced by high sky view factors and rain. Algal growth was caused by high sky view factors and significant rainfall. Application of waterproof materials on the surface to prevent water penetration should be effective. In addition, controlling the growth of trees to increase solar radiation is also effective in decreasing algae on the crest tables besides the building.

These results indicate that detachment damage is larger and more serious than damage due to algal contamination. Management to prevent detachment by controlling water supply is urgently needed.

More detailed investigations also need to be conducted to elucidate the mechanisms of deterioration, to evaluate the effectiveness of water proofing materials and mortars for conservation, and to determine management strategies for water drainage.

Acknowledgements

The information on past conservation works conducted in Koshien Hall was provided by Mr. T. Nishikawa at Nakaseki Co., Ltd. and Ms. H. Miyazaki at the Administrative Affairs Division of Koshien Hall. The drawings of Koshien Hall in Figures 1, 4, 5, and 6 were provided by Prof. H. Tembata at the Department of Architecture, Mukogawa Women's University.

Notes

1. Past preservation of Koshien Hall: In 1966 and again in 1990, preservation actions were carried out in the entire building. There is no information about the preservation in 1966. In 1990, the Nikka Stone steps on the 3F roof terrace and the central steps of the 2F rooftop (point B, Table 1) were replaced. Consolidation and waterproofing of the Nikka Stone were conducted in 2009. A report about the conservation of the Nikka Stone in Koshien Hall by Nakaseki Co., Ltd. was referred.
2. The TDR TRIME-FM3 and a surface probe by Tohoku Electronic Industrial Co.,Ltd. is used for measurement.

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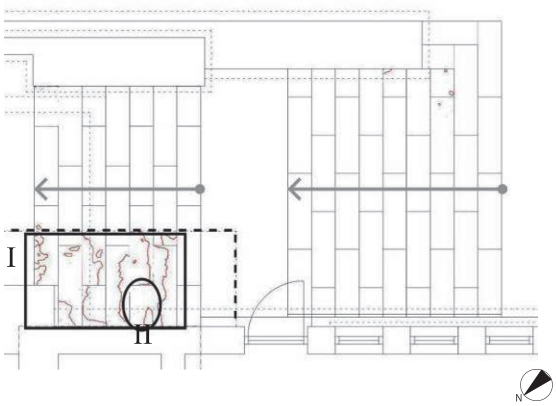
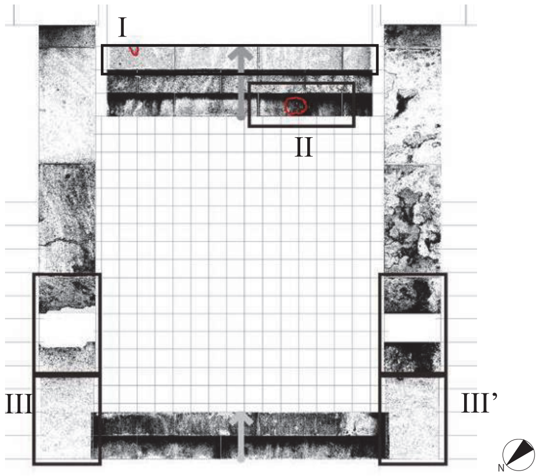
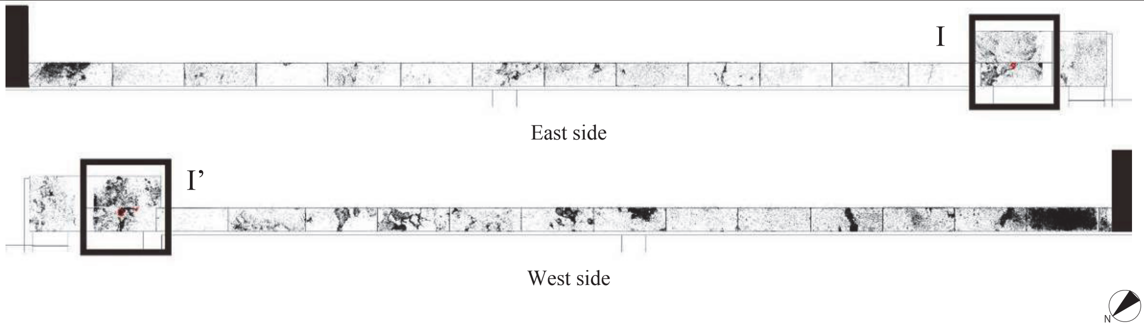
Points	Point A: West stairway of the terrace at the south side in front of the lobby in 1F	Point B: Center stairs on the 2F roof terrace
Current condition	 Detachment was observed in area I under the eaves. Notably, more than 50 % of the surface in area II is detached.	 Algal contamination was observed across the stairs and crest tables. There was large detachment in area II. Because the stones of III and III' were replaced in 2013, there is no deterioration.
Point	Point C: Crest table on the north side of the 3F roof terrace	
Current condition	 Algal contamination and detachment were observed. Algal contamination is significant in parts beside the buildings. There is significant detachment in areas I and I'.	

Figure 4. Current conditions in areas of typical deterioration at points A, B, and C

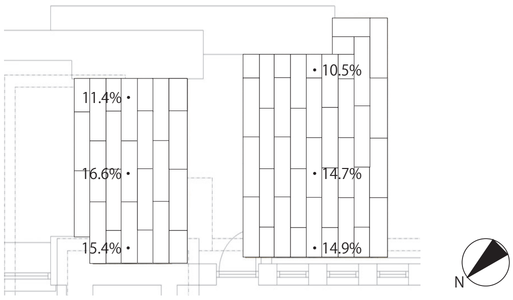
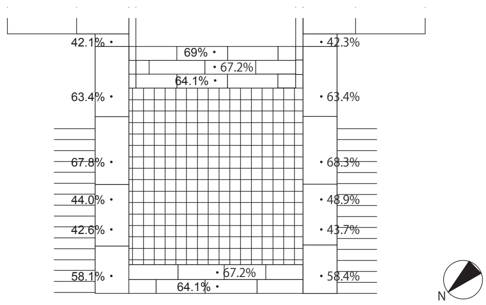
Points	Point A: West stairway of the terrace at the south side in front of the lobby in 1F	Point B: Center stairs on the 2F roof terrace
Sky View Factor	 Sky view factor was low in the entire area.	 Sky view factor was high in the entire area.
Points	Point C: Crest table on the north side of the 3F roof terrace	
Sky View Factor	 The sky view factor was high in the entire area, decreasing closer to the building. The sky view factor was higher on the west side than on the east side.	

Figure 5. Sky view factor in areas of typical deterioration at points A, B, and C

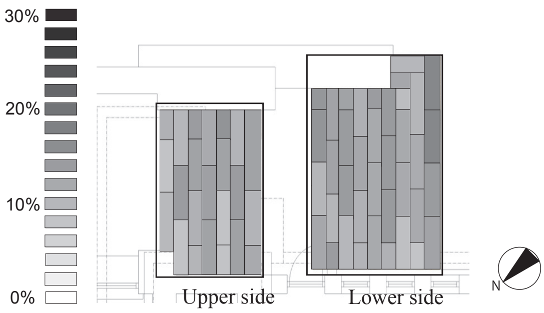
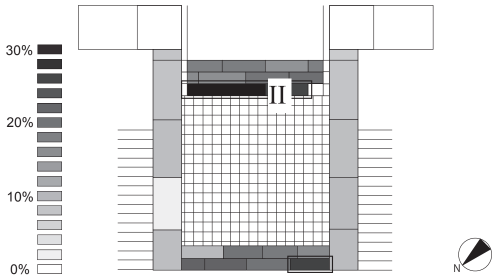
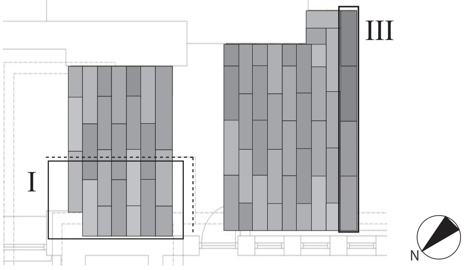
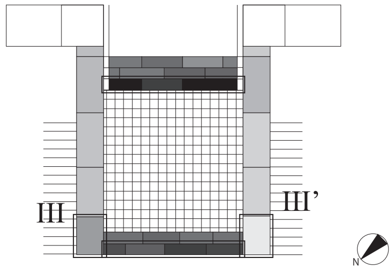
Points	Point A: West stairway of the terrace at the south side in front of the lobby in 1F	Point B: Center stairs on the 2F roof terrace
After 12-sunny days	 Water content both before and after rain was low. Water content on the upper side after rain was lower than on the lower side.	 Steps: Water content was very high. Areas surrounded by squares were saturated. Crest tables: Water content was low.
After rain fall	 Water content in area III became higher after rain, while that of area I remained low.	 Steps: Water content was very high. Crest table: There were differences in water content of each stone. Water content of the northern area III was high.
Points	Point C: Crest table on the north side of the 3F roof terrace	
After 12-sunny days	 Water content was low. Average water content on the west side was 9.3%, higher than on the east side (7.6%).	
After rain fall	 Water content was low. Average water content on the west side was 9.3%, slightly higher than on the east side (9%).	

Figure 6. Water content in cases of typical deterioration at points A, B, and C