RAINWATER ABSORPTION AND EVAPORATION COMPARED TO DEGRADATION OF WALL PAINTINGS OF HAGIA SOPHIA, ISTANBUL

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Introduction

Hagia Sophia in Istanbul, which is the authentic byzantine architecture built in the 6th century, has been suffering from severe degradation such as exfoliation of wall paintings and inner finishing materials mainly due to salt crystallization within the walls especially at the exedras of the 2nd cornice (Fig. 1 and Photo 1) [1]. Because it is important to understand the primary cause of degradation related to salt damage that is considered to be moisture accumulation and evaporation within the walls, we conducted a field survey and numerical analysis of heat and moisture behavior within the walls, with the aim of proposing a method of preservation based on physical understanding.

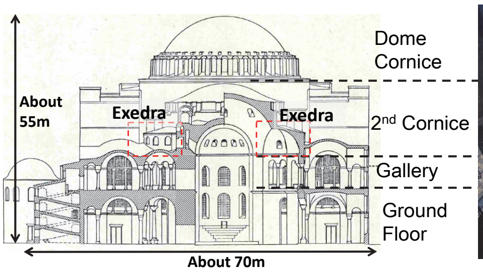

Fig. 1: Section of Hagia Sophia

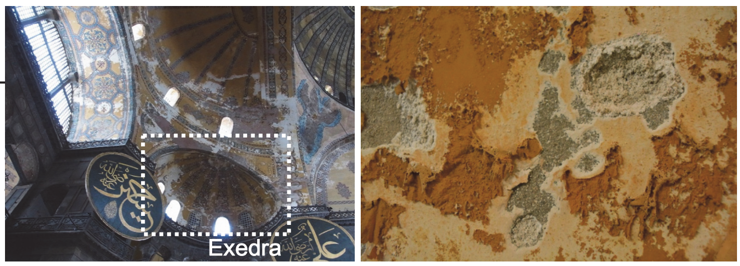

Photo 1: The northwest exedra and degradation due to salt damage

Measurement of moisture content at the 2nd Cornice

A continual deterioration survey and measurement of moisture content of the inner walls has been conducted since 2010. Fig. 2 shows the values of the moisture content measured using a contact-type TDR moisture content sensor at the 2nd cornice. The moisture content tends to be higher at the semicircular-shaped walls, i.e. the exedra. A high moisture content exceeding 20% is confirmed at the exedra in every direction. Fig. 3 shows the moisture content averaged along the inner surface of each exedra wall. The value of the northwest (NW) exedra is the highest, while the one of the northeast (NE) exedra is the lowest. Photo 2 illustrates the degradation of the walls at the NW and NE exedras; that at the NW exedra is the most terrible. As seen in [3], salt-related degradation generally corresponds to a high moisture content. At Hagia Sophia, the locations with a high moisture content are considered to be corners where rainwater runoff from the upper walls is expected (see Photo 3). Fig. 4

shows the annual cumulative amount of rainwater runoff at the walls of exedra. Judging from the roof geometry, three times the amount of the measured precipitation is assumed to be imposed on the outer walls of the exedras. The direction of exedra to which the largest amount of wind-driven rain in addition to the large amount of rainwater runoff is estimated is the NW; the average value of moisture content at the inner surface of which is also the highest. At the NW walls, it is considered that a larger amount of rainwater infiltrated the outer surface and diffused through the wall, causing a higher moisture content and a consequent severer degradation of the inner surface at the exedras.

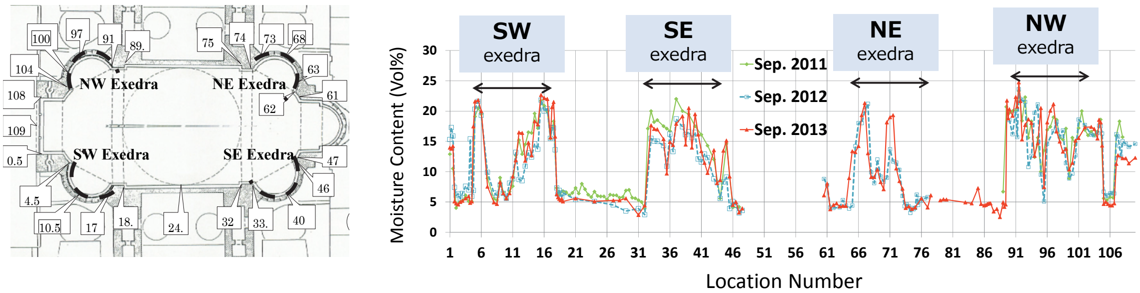

Fig. 2: The location numbers (Left) and moisture content of the inside walls measured at 2nd Cornice level (Right)

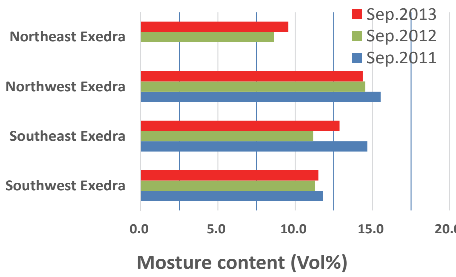

Fig. 3: Average moisture content at each exedra

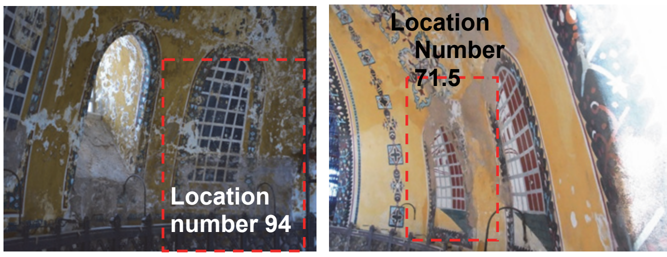

Photo 2: Degradation of the inner wall at NW exedra (left) and NE exedra (right)


Photo 3: Trace of rainwater runoff at the outer wall of NW exedra (Location number 94)

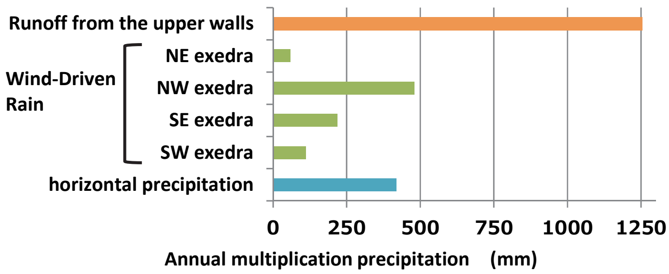

Fig. 4: Annual rainwater runoff and wind-driven rain at the exedra's outer wall surfaces

Influence of accumulation and evaporation of infiltrated rainwater

We perform a numerical analysis of heat and moisture transfer in the NW exedra wall that severely deteriorated (Fig. 5) to clarify the influence of the accumulation and evaporation of rainwater runoff from the upper walls on the degradation at exedra. The coupled heat and moisture transfer equations are solved [3]. The third kind of boundary condition is applied to the inner and outer surfaces of the walls. The temperature, humidity and precipitation measured outside and inside of Hagia Sophia every 30 minutes between September 26, 2012, and September 25, 2013, are used as the boundary conditions. The solar radiation for vertical walls facing the north is calculated by separating the direct and diffuse components of the measured total horizontal solar radiation using Bouguer's equation and Berlarge's equation. The liquid water diffusivity of the brick, connection mortar and outer finishing materials are measured for specimens exfoliated from the outer walls of Hagia Sophia. The other hydrothermal properties are taken from literature [4].

Fig. 7 shows a seasonal change of distribution of water saturation in the wall. A change in saturation is bigger at the upper part of the wall. The saturation is higher in winter and spring, i.e. the rainy season, while those are lower in summer and fall, the dry season. On the other hand, the saturation at lower part of the wall is almost saturated throughout the year, meaning that accumulated rainwater in the lower part of the wall cannot evacuate. Fig. 8 shows the spatial distribution of the evaporation rate in the inner wall of 3 m below the upper end of the wall at 0:00 on October 1. Evaporation is mainly observed to be significant between the stucco and the middle-layer mortar and between the middle-layer mortar and the brick structure consisted of brick and connection mortar. In addition, the evaporation rate at the lower part of the wall is bigger, especially between the middle-layer mortar and the connection mortar as shown in Fig. 9. Besides, those locations with the high evaporation rate generally correspond to those with severe degradation such as exfoliation of the inside stucco and the middle-layer mortar. This coincidence between the evaporation and degradation confirms a relation between the moisture evaporation and salt crystallization.

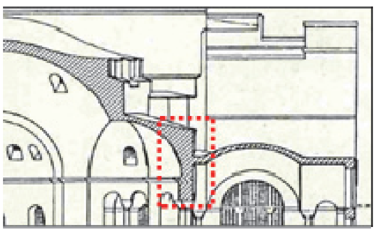

Fig. 5: The analysis modeling range

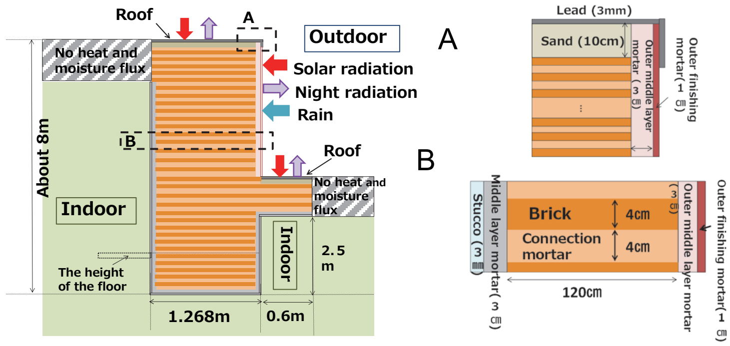

Fig. 6: Outline of the wall model and component of the walls

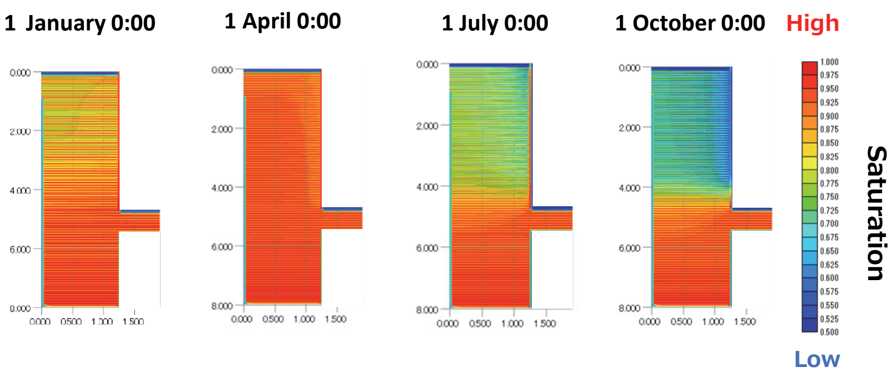

Fig. 7: Distribution of water saturation in the wall

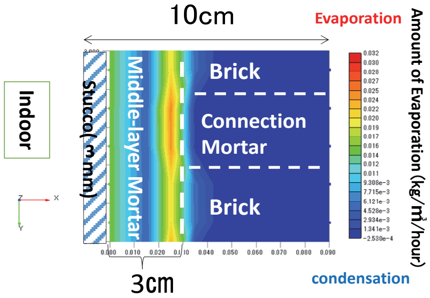

Fig. 8: Distribution of evaporation rate around the inner surface under 3m from the upper end (1 October 0:00)

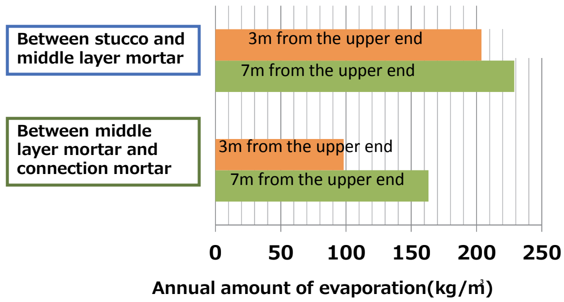

Fig. 9: Annual sum of evaporation

Conclusion

We investigated influences of rainwater absorption and evaporation on degradation of the inner walls due to salt crystallization based on field survey and numerical analysis at exedras.

The results obtained from the field survey are as follows.

-Rainwater tends to infiltrate the outer surface and diffuses through the wall causing high moisture content and consequent degradation of the inner surface at the exedras.

-It is likely that the deterioration of the inner walls at the NW exedra is attributable to more wind-driven rain in addition to much rainwater flowing down at the outer wall.

Our numerical analysis suggests the followings.

-The infiltrated rainwater flowing down the outer wall surface is accumulated especially at the lower part of the wall.

-There is a high possibility that evaporation at the boundary of the layered materials caused salt crystallization and exfoliation of the inside stucco and the middle-layer mortar.

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