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Investigation of post-restoration salt weathering at the mosaics of Dafni Monastery, Greece

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Abstract. Dafni is an 11th-century Byzantine monastery in the suburbs of Athens and a UNESCO World Heritage Site. The main church of the monastery preserves a unique complex of wall mosaics from the early Komnenian period (ca. 1100AD). The building suffered many structural problems, especially during the 1999 Athens earthquake, when the poor state of the building significantly affected the mosaics. Thus, a great restoration program was initiated. After the completion of restoration and conservation works in 2016, the mosaics presented soluble salt efflorescences and consequent disaggregation of a specific type of tesserae produced from marlstone. In order to investigate the pathology of the mosaics and study the weathering mechanisms a methodology was developed. The approach was based on non-destructive testing techniques (NDTs) combined with microclimatic monitoring and instrumental analysis. Data correlation from NDT and laboratory analyses suggests that weathering is a result of water retainment within the masonry. Depending on the microclimatic conditions, aqueous solutions evaporate through the marlstone tesserae, triggering salt weathering mechanisms.

Keywords: Dafni, mosaics, salt damage, IR thermography

1. Introduction

The Monastery of Dafni is one of the most important monuments of the Middle-Benzantine period, and it is included on the World Heritage List of UNESCO. The monastery was founded in the 6th century A.D. and its second constructional phase, dated to the end of the 11th century (around 1080), is the one preserved today. The main church is a cross-in-square octagonal-type building surmounted by a broad and high dome. The interior is decorated with superb mosaics, a unique, fine example of Middle Byzantine art. The mosaics are arranged on the dome, the cross-arms, the altar (sanctuary), and the eso-narthex of the church, while their scenes depict the life of Christ and the Virgin [1]. The building suffered much structural damage from earthquakes in 1889 and 1897, after which Italian artisans restored the mosaics and rebuilt the west side of the narthex and the dome. In 1955, a more extensive restoration project was undertaken by the Restorations Department of the Ministry of Culture, which continued until 1968.

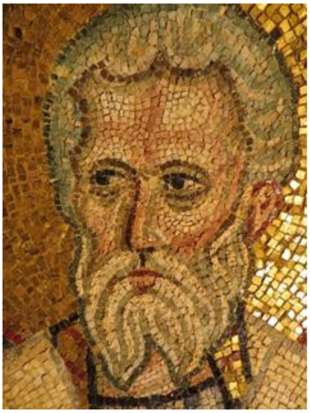


Fig. 1: The mosaic of St. Averkios has been damaged on the face (left). Salt weathering occurred only on the marlstone while the surrounding tesserae has been completely unaffected (right).

After another damaging earthquake in 1999, the poor state of the building significantly affected the mosaics. The main problem was the structural damage to the building fabric that allowed moisture infiltration, triggering a series of decaying phenomena, such as cracking and detachments, reducing the preservation state of the mosaics. A great restoration program was initiated in 2000, which, apart from the structural reinforcement of the building, also aimed to protect the interior of the building from water penetration [2]. After the completion of restoration and conservation works in 2016, the mosaics presented soluble salt efflorescences and consequent disaggregation of a specific type of tesserae produced from marlstone, while neighboring tesserae and mortar joints were not affected at all. In order to investigate the pathology of the mosaics and study the weathering mechanisms, a methodology process was developed.

The present study was performed in three steps: 1) microclimatic monitoring, 2) thermographic survey, and 3) salts analysis. The approach was based on non-destructive testing techniques (NDTs) such as Infrared Thermography (IRT), Microwave Hygrometer combined with microclimatic monitoring, and instrumental techniques such as Digital Microscopy (CMOS), Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy and X-ray Diffraction.

The mosaics investigated are located at the dome, the altar (sanctuary), and the narthex of the church. The weathering phenomena were mainly observed on the mosaics at the altar and the narthex, where humidity accumulation has been identified in the past due to water penetration. It is important to mention that salt weathering was not observed before or during the interventions.

2. Non-destructive techniques survey of the mosaics

2.1 In situ passive thermography for the inspection of mosaics

Among the different non-destructive techniques, thermal imaging can accurately obtain subsurface features information without compromising the structural integrity of the inspected target. The above along with the non-contact nature of this technique have resulted to its wide use in cultural heritage conservation field [3, 4].

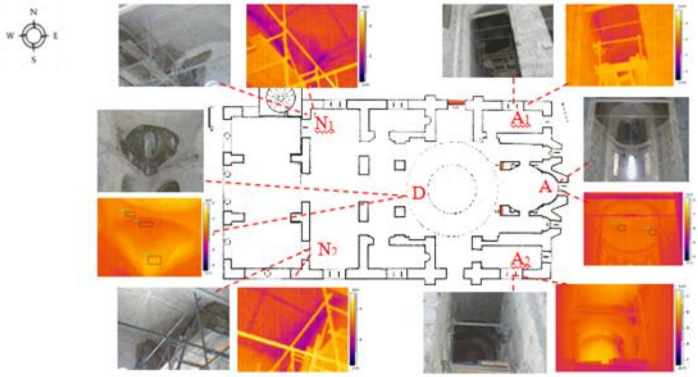


Fig. 2: Ground plan of the Monastery–Church at Dafni, illustrated by photos and thermographs.

The investigated areas of the narthex (N1, N2), the dome (D) and the altar (A, A1, A2) are highlighted with red dotted lines on the plan. Moisture was detected mainly on the stone masonry next to the mosaics of the narthex and on the northeast (A1) and southeast (A2) apses of the altar. The mosaics investigated on the angular imichonia of the dome (D) showed thermal uniformity.

In the present study, the passive infrared thermographic investigation was performed using a ThermaCAMTM SC640 long-wave thermography system (7.5 – 13 μm). The mosaics investigated are located on the angular mahonia (squinches) of the dome, on the apses of the altar (sanctuary), and on the upper walls of the narthex. The altar is situated at the east part of the church, while the narthex is located at the west end.

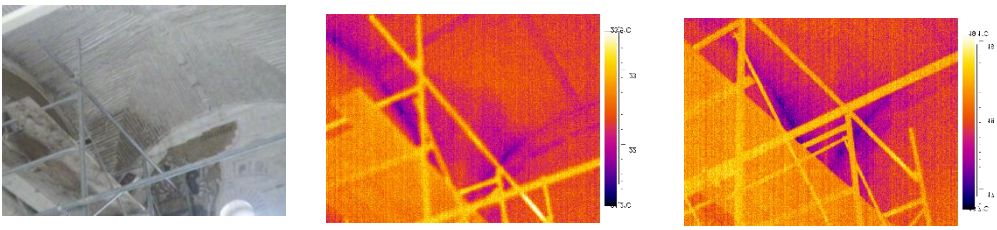


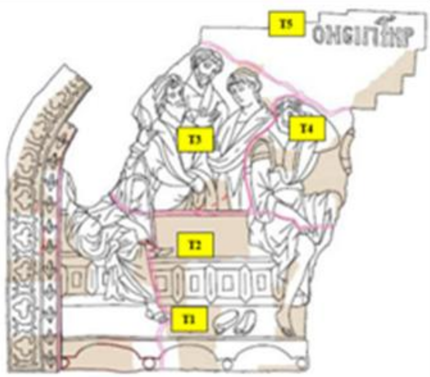
Fig. 3: View of the northwest area of the narthex, where the mosaics 'Betrayal of Judas' and 'Washbowl' are located (from left to right), visible light photo, thermal image taken in September and thermal image taken in November. The suspected wet areas are visible in these thermographs as blue, while dry areas are presented as red and yellow. The color bar shows the measured temperature range.

The wall-mosaic surfaces were scanned in segments by taking single IR images together with their visible-light photographs, as shown in Figures 3-4. The IRT tests were performed during daytime hours over repeated cycles for a six-month period (July-November 2016). The main

purpose of this survey was to monitor any spatial variations of the surface temperature distribution in order to detect moisture accumulation on the wall mosaics.
Representative thermal images and digital photos of some areas of the monastic building are illustrated together in Figure 3. Temperature variations were observed mainly on the stone masonry next to the mosaics of the narthex and on the apses of the northeast and southwest parts of the altar (sanctuary). Thermographic investigation of the mosaics on the angular imichonia (squinches) of the dome showed temperature uniformity that indicates the absence of moisture accumulation.
More specifically, the thermographic image taken on the north side of the narthex in September and November additionally showed thermal variations on the stone masonry, mainly next to the mosaic depictions of the 'Betrayal of Judas' and the 'Washbowl' (Figure 4). In Figures 4b,c, the suspected wet areas are relatively cool and clearly visible in these thermographs as blue areas, while warmer-dry areas are presented as red and yellow. Moisture was also detected on the stone arch next to the mosaic of 'Saint Avercios', which is located at the southeast part of the altar. Nevertheless, in this case, the suspected wet areas were limited (Figure 3 A2).

2.2 In situ moisture measurement of mosaics substrate

A non-invasive microwave hygrometer (Protimeter MMS) was used to measure the mosaic subsurface moisture content. The wall-mosaic surfaces were scanned by taking several spot measurements, as shown in Figure 5. The tests were performed during daytime hours over repeated cycles for a six-month period (July-November 2016). The main purpose of this survey was the monitoring of moisture levels in the wall-mosaics subsurface. The results were evaluated comparatively. Representative images and plots of moisture content data collected per test period are illustrated together in Figure 5.



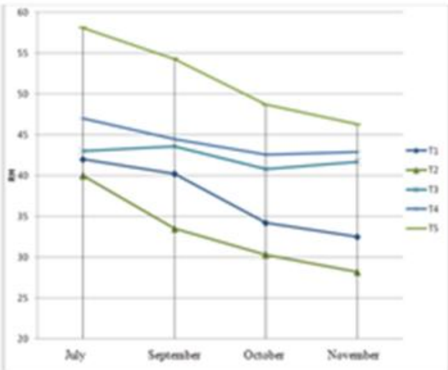


Fig. 4: Drawing of the mosaic 'Betrayal of Judas' where the areas measured are highlighted by yellow color (left) plot of RH data per test period (right).

Results obtained show that the moisture content of mosaics substrate is decreased gradually. The indoors atmospheric temperature and RH were continuously monitored for a six months period by means of data loggers. During this period there was no evidence of dew formation.

3. Salt Weathering Analysis

3.1 Microscopy and Microanalysis of salts

Microscopic in situ observations by means of digital microscopy (CMOS) revealed that the damaged tesserae partially maintain their external surface while the internal pore system has collapsed. The surrounding mortars were completely intact, and the salt efflorescence contained particles that probably derived from the disintegration of the tesserae. It was also evident that damage had already advanced to a point where consolidation would not be plausible. These preliminary fast observations dictated the sampling strategy. The samples from the damaged areas were analyzed by EDAX, while samples for crystallographic analysis were collected from surrounding efflorescence, which was clear of disintegration particles.

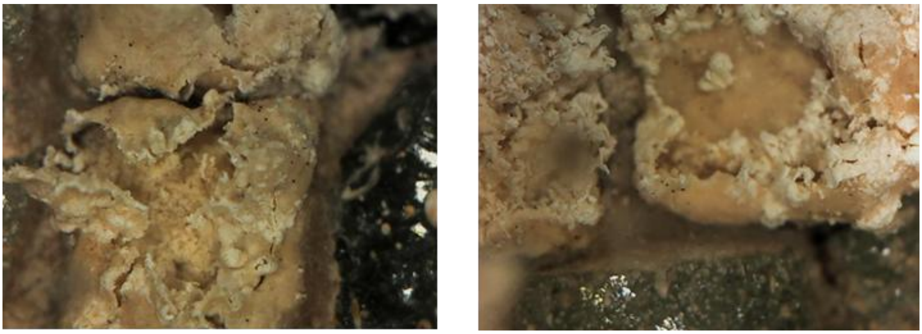


Fig. 5: Microphotographs of the marlstone tesserae show internal sand disintegration.

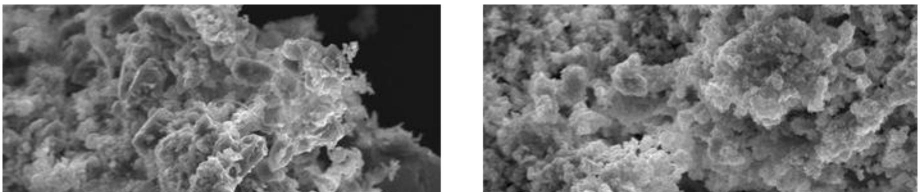


Fig. 6: SEM photographs of salt efflorescence from the damaged tesserae. The efflorescence is a mixture of tesserae disintegrated particles and sulphate salts.

Sampling took place at the maximum temperature, and thus, we presume that the majority of salt species were collected. The SEM-EDAX results from the damaged areas are consistent and reveal high concentrations of sulfur, mainly related to calcium, followed by magnesium and, in some cases, sodium. The salt crystals are amorphous and they are mixed with calcareous and quartz particles. The salt crystals were highly unstable during analysis, indicating hydrated species. The efflorescence samples from other areas contained various elements such as sodium, chlorine, and calcium. The results of the crystallographic analysis of the damaged areas identified gypsum, quartz, and calcite. XRD analysis of the marlstone tessera identified the presence of magnesite.

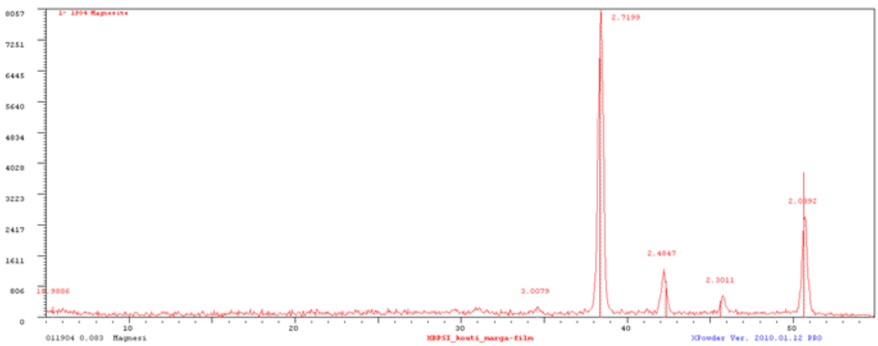


Fig. 7: XRD spectrum of undamaged marlstone identified the presence of magnesite.

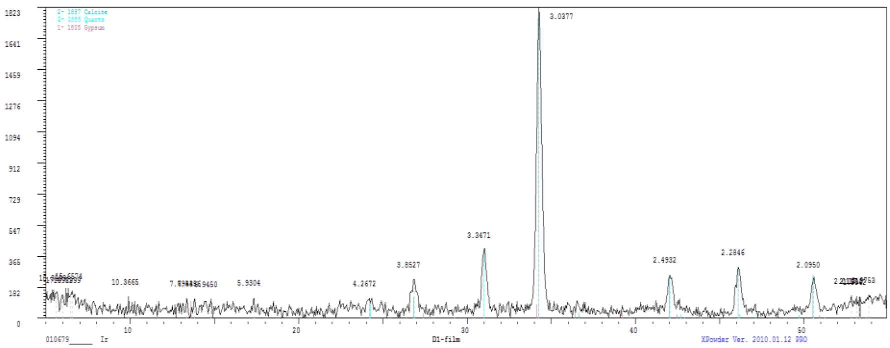


Fig. 8: XRD spectrum of efflorescence from damaged tesserae.

Discussion

Data collected from the IR- Thermography suggests the existence of areas on the interface of mosaics and wall masonry suffering from moisture accumulation. However, in order to gain the best possible understanding of the detected thermal effects and the best possible interpretation of the acquired results, a thorough knowledge of the history of the investigated structure is required. The affected mosaic areas present high moisture accumulation and have been treated in the past with cement grouts. Apparently, the climatic conditions during the restoration interventions of the monument have not been appropriately considered. Taking into account the scattered surface temperature variations of the wall masonry, we can assume the existence of water accumulation in the masonry during the restoration works. The moisture front has been directed towards the internal surfaces of the masonry, which evidently provided a more effective evaporation site.

The presence of gypsum in monuments is connected to various sources but mainly air pollution to external surfaces, pesticides, marine aerosols, and, in some cases, restoration cement [5]. In this particular case, the presence of sulfates is more likely related to previous restoration works since there is no evidence of any other active source. Sulfate contained in cement grouts can be released gradually over a period of time due to the delayed carbonation of ettringite [6]. Magnesium probably derives from the building materials while the investigated tesserae contain magnesite as well.

Although the monument is close to the sea, the presence of chlorides cannot be related to the direct deposition of marine particles due to insufficient entry points. Still, the infiltration of rain waters, which in this environment might be enriched in chlorides, could be an effective source. Contrary to sulfates, which usually crystallize first, chlorides might be transported to the surface more easily.ref The continuous presence of moisture and indoor evaporation have probably permitted the salts to transport toward the surface of the mosaics without whatsoever any evidence of damage in these areas.

The damaged areas are mainly affected by less soluble salts. Even in conditions with high moisture content of the building materials, their transport is quite restrained, and they present few crystallization and dissolution cycles. Still, gypsum presents several phase transitions to hydrated states. According to environmental data, dehydration, and rehydration cycles could take place before the occurrence of damage. Damage phenomena were evident at the surface, probably later than the initiation of internal disintegration. We can suppose that since no other efflorescence was evident in the proximity, the particular marlstone tesserae were porous enough to permit moisture penetration.

Nevertheless, salt infiltration alone does not necessarily justify the generation of damage. Porosity is the only evident variable that distinguishes marlstone from the adjusting tesserae, while the salt species and the environmental conditions are common. The pore structure of marlstone is theoretically responsible for the intensity of damage since it is composed of pores of various sizes [7], but more research is needed in order to argue soundly on the generation of damage. The conditions of damage gradually declined, and evidently, there were no other damage phenomena or salt efflorescence during the next period.

Conclusions

The investigation related very rapidly moisture content to damage phenomena, indicating the necessary actions ahead. The potential of more damage to other areas has been excluded providing time for further research. Also we avoided unnecessary and potentially harmful treatments like desalination or consolidation that are usually performed as immediate measures.

The mobilization of salts has been triggered by trapped moisture during restoration works. The moisture front has been directed to the internal surfaces even during high-temperature outdoor conditions, probably due to the external consolidation of the monument with low porosity mortars. The generation of damage that affected a specific tesserae type can be attributed to the hydration-dehydration cycles of gypsum. The role of the pore properties of the tesserae is also under investigation, although the surrounding tesserae consist of either glass or very low porosity stones.

Still, it was evident that damage was an individual incident that was receding with the evaporation of the trapped moisture and probably it would not occur periodically. Thus no

further interventions like desalination or cleaning needed to take place. The environmental conditions are still monitored and thermography investigations will take place in longer intervals for precautionary measures.
Post treatment evaluation is necessary in extended conservation works. This evaluation must depend on fast and reliable techniques in order to avoid damage phenomena. Especially in the case of salt damage which can act undetected under the surface of the monument, evaluation should take place immediately after the completion of conservation. Evaluation should definitely include fast temperature readings like digital thermography as well as selective moisture investigation since they can easily detect non-uniform areas and alterations that might be indicative of potential problems.

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