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Study of the historical mortars of the Holy Aedicule as a basis for the design, application and assessment of repair mortars: A multispectral approach applied on the Holy Aedicule

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HIGHLIGHTS

- Different lime-based and gypsum-based mortars determined in the Holy Aedicule.
- Criteria are set to select a compatible and performing restoration mortar.
- NDTs are used to examine the historical and restoration mortars on monument scale.
- Analysis and evaluation throughout all stages of a restoration project.
- An integrated methodology for complex monuments' rehabilitation is presented.

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ABSTRACT

The rehabilitation of the Holy Aedicule of the Holy Sepulchre in Jerusalem, completed in March 2017, aimed to address the deformation problems encountered after its most recent reconstruction in 1810. A diagnostic study performed by the National Technical University of Athens (NTUA), indicated the cause of the deformations and revealed the Aedicule's structural layers. The results permitted the design, selection and application of compatible and performing restoration mortars, while the assessment of their application was achieved through a multispectral approach and in combination with an integrated analysis throughout the rehabilitation project. The results acquired through analytical and non destructive techniques show that compatibility was ensured and the structure was adequately strengthened and concludes in a methodological approach regarding all stages of a rehabilitation project of a complex multilayered monument.

1. Introduction

The study of a monument's historical mortars prior to any restoration interventions is crucial, both for the determination of the decay mechanisms its building materials are subjected to, as well as for the establishment of the demands which a restoration mortar should fulfill in order to achieve compatibility and at the same time the desired performance. Compatibility, in international literature, is assessed in terms of a material having no negative impact on the historical materials and the structure as a whole, whilst performance is interlinked with the improvement of the structure to sustain static and dynamic loads. Thus, compatibility of the restoration mortar can be addressed in relation to the historical mortars of the masonry, through a reverse engineering methodological approach, and assessed in relation to all building elements of the structure by achieving a homogenous mechanical and hygric behavior [1–7]. Performance of a restoration mortar is linked with compatibility criteria and is evaluated through the improvement of the dynamic behavior of the structure as compared to its original state [8]. During the restoration mortar design and selection process, compatibility and performance are assessed on material level through analytical techniques (physical-chemical, mechanical characteristics) and on monument level

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through computational methods (e.g. finite element analysis). In parallel, Non Destructive Techniques (NDTs) play an important role in the field of monument protection, as they are widely used in diagnostic studies on monumental scale, as well as for the assessment of restoration interventions [9–11].

The Holy Aedicule of the Holy Sepulchre in Jerusalem is the structure enveloping the holiest site of Christianity, what is believed to be the Tomb of Christ, the place where he was buried and the site of His resurrection. The Holy Aedicule evolved and transformed throughout the centuries, changing in form, size and shape. From a typical hewn rock tomb of the 1st century CE, the Tomb of Christ transformed into a ciborium type structure (Aedicule) enveloping the rock tomb during the reign of Constantine the Great in the 4th century [12]. Throughout the centuries, the Holy Aedicule sustained many damages (deliberate destructions, destructive earthquakes, fires) and consequent restorations and reconstructions, while it expanded to the east when the Crusaders added an ante-chamber, the Chapel of the Angel, in the 12th century [13]. The latest reconstruction was implemented in 1809–1810 by the Architect "Kalfas" Komnenos, after a great fire broke out in the Rotunda area, severely damaging the external facades of the Aedicule [14,15]. Komnenos allegedly "rebuilt" the Aedicule, as stated in the engravings on the marble slabs enveloping it, although recent findings indicate that he incorporated many parts of the older Aedicules within his new structure [16]. In 1947, the Komnenos Aedicule had started to show serious displacements and deformations [17]; the observed buckling of the marble slabs and the intense deviation from verticality led to the installation of an iron grid from the British Mandate in order to avoid collapse of the structure. In 2015, after invitation of his Beatitude, Patriarch of Jerusalem Theophilos III, the National Technical University of Athens (NTUA) Interdisciplinary Team for the Protection of Monuments, performed an "*Integrated Diagnostic Research Project and Strategic Planning for Materials, Interventions Conservation and Rehabilitation of the Holy Aedicule of the Church of the Holy Sepulchre in Jerusalem*" in order to examine the observed damages and deformations, explain their cause, and propose appropriate measures to restore the structure [18]. Soon after the completion of the diagnostic study, and based on the results and the restoration materials and interventions proposed, the Holy Aedicule's rehabilitation project began, supervised by NTUA interdisciplinary team, after the Common Agreement of the three Christian Communities responsible for the Holy Sepulchre. The rehabilitation of the Holy Aedicule was completed within 9 months, allowing for the Holy Light Ceremony to proceed as usual, which was a prerequisite placed for the execution of the project by the leaders of the three Christian Communities responsible for the Protection of the Tomb of Christ according to the Status Quo [19]. The aim of the restoration project was to achieve sustainable rehabilitation, ensure structural integrity of the structure, whilst preserving all the values that this unique monument carries [20].

The diagnostic study, in addition to the scientific supervision of the project by the interdisciplinary NTUA team, provided a unique opportunity to study the structure and its historical materials, as well as to assess the materials and interventions used for its rehabilitation, employing scientific support in decision making in practice. In the current paper, the results from the study of the historical mortars of the Holy Aedicule are presented as a basis for the design, application and assessment of compatible and performing restoration mortars. The multispectral approach, through the combined use of analytical and non destructive techniques, applied throughout all stages of the rehabilitation project, proves extremely useful in the decision making process regarding the selection of materials and interventions, as well as in the evaluation process of the behavior of the restoration mortar on the actual structure in real time conditions, and concludes in an integrated methodology, which can be applied on other important monumental complex structures. The Holy Aedicule, due to the complexity of the structure and the role of the mortars in the dynamic response of the structure and its state of preservation, serves as an ideal case study for the illustration of this approach.

2. Materials and methods

A variety of analytical techniques were employed to study the historical mortars of the Holy Aedicule, as well as different restoration mortars. The mineralogical composition of the materials was examined through X-ray diffraction (XRD) using an Advance D8 Diffractometer of Bruker Corporation [21–23]. Differential Thermal and Thermo-Gravimetric Analysis (DTA-TG) was employed in order to attain qualitative and quantitative information regarding the composition of the mortar samples in static atmosphere within a temperature range of 25–1000 °C with a heating rate 10 °C/min, using a 409 EP, Netzsch [22]. Mercury Intrusion Porosimetry (MIP) was employed to study the microstructural characteristics of the historical and restoration mortars, as well as the building stones, using a Pascal 400 Thermo-Electronics-Corporation [21,24]. Sieve analysis was performed on selected mortar samples, according to Normal 27/88 [21] using sieves in accordance to ISO 565, aiming to separate the mortar fractions and analyze the production technology, as well as to analyze grain size distribution of the aggregates and calculate the ratio of binder to aggregates. Total Soluble Salts Measurements were conducted, in accordance to the guidelines of Normal 13/83 [25], in order to estimate the concentration of total soluble salts in the mortar samples; spot test were also undertaken to acquire qualitative and semi-quantitative information regarding the type of salts present.

Non destructive techniques were employed during the diagnostic study, as well as throughout all stages of the rehabilitation project, aiming to study the *compatibility* of the historical building materials, ascertain which environmental factors are affecting the building materials and detect problematic areas, as well as to assess the effectiveness of the restoration mortars in terms of compatibility and performance on masonry level. NDTs included Infrared Thermography (IRT), using a FLIR Systems Therma Cam B200, Ground Penetrating Radar (GPR), using a MALA Geoscience ProEx with a 1.6 GHz antenna and Ultrasonic Measurements (UPV), using a Pundit PL-200PE.

3. Results and discussion

3.1. The Holy Aedicule structural layers

The Holy Aedicule is an indoor monument, located in the center of the Rotunda in the Church of Resurrection. It is a complex structure, enclosed within stone facings, with no access or visibility of any internal structural layers. As mentioned above, the Holy Aedicule presented displacements of the columns and intense buckling of the stone slabs of the facades (Fig. 1). Non-destructive testing was implemented to reveal the structural layers of the Aedicule by coupling the results of a ground penetrating radar (GPR) campaign with architectural analysis [26]. The results revealed a truly complex structure with internal layers and even remnants of the Holy Rock embedded within an internal masonry at the north and south side of the western chamber (i.e. the Tomb Chamber). The layers of the Aedicule from the exterior to the interior are: exterior stone facings, filling mortar layer, masonry, Holy Rock (only around the Holy Tomb Chamber), filling mortar layer and interior marble facings (Fig. 2).