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A methodological approach for the selection of compatible and performable restoration mortars in seismic hazard areas

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HIGHLIGHTS

- Compatibility and performance criteria from historical mortar characterization.
- Lime-metakaolin mortars present compatibility and range of mechanical properties.
- Fragility analysis for mortar performance assessment under earthquake stresses.
- Methodology for the selection of restoration mortars in seismic hazard areas.

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ABSTRACT

The application of restoration mortars in historic structures is the most usual conservation action. A methodology is herein established to extract compatibility and performance criteria utilizing the study of the historical structural materials of a monument and the results of fragility analysis. Thus, it is possible to evaluate restoration mortars' compatibility and performance, through compliance with the set criteria and select the optimum material for earthquake resistant design of masonry structural systems in seismic hazard areas. The byzantine Catholicon of Kaisariani Monastery is utilized as a case study in order to illustrate the applicability of the methodology. The methodology can serve as a tool for decision making within a scientific framework.

1. Introduction

The conservation and restoration of historical buildings and monuments is crucial in order to preserve our cultural heritage. Historical materials deteriorate due to natural weathering, corrosive environments, natural phenomena such as earthquakes, as well as human actions, such as the use of incompatible restoration materials. The use of incompatible conservation and restoration materials intensifies or even initiates decay mechanisms and can lead to catastrophic results [1–5]. Thus, in recent years research regarding the design and selection of the appropriate restoration materials and techniques is interlinked with compatibility assessments in order to ensure the long-term durability of monuments and historical structures [6]. The most usual restoration action implemented on monuments and historical buildings is the application of new restoration mortars. This is attributed to many factors; the mortars are usually more susceptible to decay factors in comparison to stones and bricks –partially due to their role as protective and sacrificial elements– and therefore substitution is necessary; the application of restoration mortars is less costly than the substitution of carved stones or bricks; the application of restoration mortars offer the option of reapplicability and retreatability [2,7,8]. In the past decades reversibility of any intervention was considered a mandatory criterion, however, rather than reversibility, the recent tendency regarding the application of restoration mortars is the achievement of compatibility and retreatability. Thus, most researches regarding the design and selection of new restoration mortars also include the assessment of their compatibility for use in historical structures [7,9–13]. Retreatability is interlinked with compatibility, as it refers to the application of a restoration mortar that does not jeopardize future treatments [7,8].

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Compatibility, which is the focal point in every new restoration mortar assessment, is a complex term. Many researchers define compatibility as the opposite of incompatibility, therefore a compatible mortar is not incompatible and does not induce any king of damage to the other building elements of a masonry [6–8]. The parameters determining compatibility can differ slightly between researchers; however the main categories refer to aesthetic, chemical, physical and mechanical compatibility and are usually determined in relation to the similarity of the restoration mortar and the historical mortar of the masonry [7,9–13]. The requested result is the achievement of a homogenous mechanical and hygric behavior between the different building materials of the masonry and the ensurance that no degradation mechanisms will be induced by the application of the restoration mortar [2]. Compatibility assessments are usually conducted in regards to the historical mortars or the substrate they are to be applied to [7,9–13].

During the selection of the optimum restoration mortar which will be applied for the restoration of a historical building, compatibility of the restoration mortar must be ensured with both historical mortar and building elements of the masonry, as the historical mortar will usually be replaced only to a certain extent and will therefore remain within the masonry, and the building elements must not be altered or deteriorated by the use of the new restoration mortar. In addition, the mechanical performance of the restoration mortar must also be taken into account, as mortars are an essential part of the masonry, undertake stresses and affect the mechanical behavior of the masonry as a whole. This is especially the case in thick joint masonries, where the excellent long-term behavior of certain monuments in seismic hazard areas is attributed to the correct design and good quality of the structural mortars used for their construction [14,15]; mechanical performance of the restoration mortar is an issue of great importance which cannot and should not be overlooked. Hence, restoration mortars with characteristics as similar as possible to those of the materials to be repaired should be searched out, at the same time optimizing mix designs in order to achieve both the demanded compatibility and the required level of mechanical performance. Environmental factors which affect the monument must also be taken into account, as they affect the longevity of the materials [16,17].

A methodology which has proved helpful in rediscovering traditional mortar production technologies and designing compatible restoration mortars is reverse engineering [1,2]. Thus, by discovering the ancient technology employed for the production of the original mortars, new, compatible restoration mortars can be designed. The most important steps that must be followed, are i) sampling of representative mortar samples, selecting the mortars that exhibit the least possible decay (environmental, physical, mechanical), ii) characterization of the historical mortar through various techniques and classification in order to determine the range of acceptability limit values which must be set for the restoration mortars and iii) design of proper restoration mortars and assessment [2]. Thus, restoration mortars designed through reverse engineering are based on traditional technologies and can achieve a high level of compatibility with historical structural elements.

During this procedure it must be taken into account that the results from the analysis of the historical mortar is only a starting point. Due to the degradation of the historical mortars of a monument or historical building and due to the limited amount of samples which can be obtained by important structures due to limitations (legislation, preservation of values etc.), the results from historical mortars analysis lack statistical certainty. Thus, the measured values of historical mortar characteristics cannot serve as absolute values for the restoration mortar selection, but rather as the correct direction which the design/selection of the restoration mortar must follow. Through the analysis of a great number of historical mortars, the Laboratory of Material Science and Technology, School of Chemical Engineering, National Technical University of Athens, has achieved the grouping of historical mortars and the determination of acceptability limits which restoration mortars must fulfill, taking into account the characteristics of historical mortars which have presented great resilience and durability throughout time and have proven to be compatible and performing in service in masonries, in real time and real conditions [18,19]. Thus, the results from the analysis of a historical mortar can lead to its classification and the restoration mortar can be selected through mortar mixes which comply with the set acceptability limits.

In the current study, an integrated approach is adopted, aiming to set a methodology for the selection of the optimum compatible and performing restoration mortar for restoration interventions of historical structures in seismic hazard areas. The methodology is illustrated through utilizing the case study of Kaisariani Monastery. The results from the analysis of the historical mortars and other building materials are used to set compatibility criteria that the restoration mortar must comply with [20–22]. Restoration mortars, designed by the same research team in previous studies through the reverse engineering methodological approach [23,24], are then selected and specific characteristics of the restoration mortars are examined in order to assess compliance with the set compatibility criteria, in accordance to the proposed methodology. The impact of the selected restoration mortars on the earthquake resistance of the structure is then evaluated through the use of fragility analysis for different repairing scenarios, in order to accomplish the selection of the optimum restoration mortar for the earthquake protection of the monument.

The Catholicon of the Kaisariani Monastery is a typical mid-byzantine Athenian church structure, built in the late 11th or early 12th century. Originally it was a complex cross-in-square four-column domed church. Throughout the centuries a narthex was added to the west and a chapel was added to the south (Fig. 1). The building materials consist of carved stones, bricks and mortars. The east façade is a typical cloisonné type masonry, considered original. The church has undergone restoration interventions; two important restoration projects took place at the complex in the beginning and the middle of the 20th century, however without adequate documentation of the work implemented [25-27].

2. Methodology, methods and techniques

In the current study a methodological approach is set in order to assist in the selection of the optimum restoration mortar for restoration interventions of a historical structure in seismic hazard areas. Compatibility criteria, regarding chemical, physical and mechanical compatibility of the restoration mortar with the historical mortars and the other building elements of the structure, as well as performance criteria, regarding the resilience of the restoration mortar in the environment of the monument and under seismic stresses, are set through the combined analysis of the historical mortars, other building elements of the structure, such as bricks and stones, environmental factors affecting the monument, as well as other restrictions in regards to safety requirements. Fragility analysis is conducted as the final step of the methodological approach, in order to assess the contribution of the restoration mortars to the improvement of the mechanical performance of the structure in earthquake stresses, in seismic hazard areas (Fig. 2).

Specifically, in the present research, the following steps were realized: