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Assessing material compatibility for restoration: An innovative approach to compare hydraulic properties of repair and historic mortars

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Abstract – **This study compares the hydraulic properties of historic and experimentally reproduced mortars to assess their compatibility and performance in restoration contexts. Mortar replicas have been prepared by using traditional recipes from Catania (Sicily, Italy), where ghiara, a red volcanic aggregate from altered paleo-soils by Mt. Etna, is commonly used. Two formulations with different aggregate grain sizes (with and without the <0.063 mm fraction) were tested to assess hydraulic behavior. These were compared with mortars sampled from a historic masonry wall in Catania, which showed variability in color and aggregate grain size. Hydraulic phases were identified using Q-XRMA software, which applied PCA and supervised classification to SEM-EDS maps. Additionally, the GIS-based MFA tool characterized aggregate features in historical samples. Experimental mortars showed enhanced hydraulicity (~90% binder as moderately hydraulic lime to cement), while those from the historic masonry displayed more variable pozzolanic properties, likely due to past restorations.**

I. INTRODUCTION

Modern conservation practices emphasize the importance of using repair mortars that are chemically, physically, and mechanically compatible with original materials to prevent damage from mismatches. A significant challenge lies in designing new mortars that closely replicate historical ones in composition, texture, porosity, and strength [1, 2]. Laboratory reproduction of historical mortars allows researchers to investigate the effects of raw material selection, such as the type of lime, aggregate grain size, and pozzolanic additives, under controlled conditions. This approach facilitates the assessment of mechanical properties, water behavior, and microstructural evolution, contributing to the development of sustainable and compatible mortars for heritage conservation [2].

Recent developments in micro-scale analytical techniques have opened new perspectives on the study of mortars, especially in unraveling the processes that govern the generation of hydraulic compounds like calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH) phases. The role of aggregates as potential catalysts in these reactions has proved to be particularly relevant. Yet, despite these advances, the fine-scale and irregular nature of such transformations continues to obscure the reasons behind the enhanced performance observed in certain mortars compared to others [3, 4]. A variety of standard analytical methods, such as X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), X-ray Fluorescence Spectroscopy (XRF), and Scanning Electron Microscopy combined with Energy Dispersive X-ray Spectroscopy (SEM-EDS), are commonly used to investigate the presence of hydraulic components in historical mortars and to evaluate their degree of hydraulicity. Despite their widespread use, these techniques have intrinsic limitations. To address such analytical constraints, recent advancements have turned toward digital image analysis tools, increasingly coupled with Geographic Information Systems (GIS) and multivariate statistics like Principal Component Analysis (PCA) [5]. These innovations allow to manage large, spatially resolved datasets and to isolate mineralogical features within thin sections with high precision, all while retaining their contextual relationships. By leveraging the spectral richness of EDS elemental maps and applying PCA, researchers can more effectively highlight subtle chemical variations and pinpoint zones of localized hydraulic reactivity with greater objectivity and quantitative rigor. In addition, recent methodological developments have introduced GIS-based grain size analysis as a powerful tool for the spatially resolved quantification of microstructural features in geomaterials [6]. This approach enables the precise spatial characterization of aggregate distributions, offering a deeper understanding of how particle size and sorting influence the physical and mechanical behavior of the material. Unlike traditional granulometric methods, GIS-assisted analysis preserves the spatial context of the aggregates within thin sections, allowing researchers to

relate microstructural features to performance attributes in a more detailed and systematic way.
Within this methodological framework, the present study focuses on historical lime-based mortars from the city center of Catania (Sicily, Italy), where ghiara, a red volcanic aggregate derived from altered paleosoils of Mt. Etna, is commonly used. By reproducing these materials in the laboratory and analyzing both experimental and historical samples using innovative micro-analytical tools, this research aims to contribute to the design of sustainable and compatible repair mortars for heritage conservation.

II. MATERIALS AND METHODS

Some mortar samples were collected from an external masonry wall of a historic building located in the city center of Catania (Sicily, Italy). These mortars, composed of lime putty mixed with ghiara, are representative of the construction materials most commonly used in the city's historical architecture. The selected samples exhibit a certain macroscopic variability, particularly in terms of color intensity (with varying shades of red) and aggregate grain size distribution (Figure 1). To gain deeper insight into the composition and variability of the historical mortars, the collected samples were analyzed using an integrated analytical approach, including polarized light optical microscopy (PLOM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR), for detailed mineralogical and petrographic characterization.

Concerning the preparation of the experimental mortars, a commercially available ready-made slaked lime was used as a binder. The aggregates consisted of ghiara sand collected from the Perniciaro quarry, located near the town of Belpasso, in the province of Catania (37°33'45.60"N 14°59'40.10"E). The mortar formulation was based on a historical recipe documented in the literature [7], applying an aggregate-to-binder ratio of 3:1. Two different mixtures were prepared: the first (MG1 series) included aggregates ranging from 2 mm down to the finest fraction below 0.063 mm, while the second (MG2 series) contained only aggregates between 2 mm and 0.063 mm (Table 1), to assess the potential influence of this fine component on the physical, mechanical, and hydraulic properties of the mortars.

Table 1. Characteristics of experimental mortars.

Series	Grain size of aggregate	Aggregate/binder vol. ratio
MG1	$\phi \leq 2$ mm	3:1
MG2	2 mm $\leq \phi \leq$ 63 µm	

The reproduction process of the experimental mortars began with the mixing of ghiara with aerial lime and water. The mixing was carried out at room temperature, and the resulting paste was poured into molds of standardized dimensions. To eliminate air bubbles and ensure homogeneity, the molds were placed on a vibrating table (Figure 2).

Fig. 1. Sampling sites of ghiara mortars in the historic city center of Catania (Sicily, Italy).

The specimens were then cured at room temperature for 28 days, under conditions of relatively high humidity to promote proper carbonation and hardening of the lime-based binder. The specimens were subjected to a multi-analytical investigation aimed at evaluating their physical and mechanical properties. The analytical program included mineralogical characterization by X-ray diffraction (XRD), petrographic analysis of thin sections under polarized light microscopy (POM), water absorption tests (by capillarity and under atmospheric pressure), Vicat's needle test, as well as uniaxial compressive strength and surface hardness (perforation resistance) measurements. This integrated approach enabled a detailed characterization of the reproduced mortars and their performance, with particular attention to the role of aggregate granulometry and the presence of fine volcanic fractions.

To enable a comparative evaluation between historical and experimental mortars aimed at assessing their hydraulic behavior, a GIS-based image processing approach was employed using the Quantitative X-ray Map Analyser (Q-XRMA) software [5]. High-resolution X-ray elemental maps (approx. 2 μm per pixel) were acquired from two representative micro-domains for each mortar type and subsequently processed to investigate the influence of aggregate grain size on the reactivity with the surrounding binder matrix. The Q-XRMA workflow here applied includes three steps: (i) phase classification, (ii) subphase segmentation, and (iii) creation of hydraulicity index maps through a kernel density function. This study focused on the binder to detect subtle compositional variations. First, PCA was applied to elemental X-ray maps to enhance phase separability and reduce data redundancy. The resulting images were classified using Maximum Likelihood Classification (MLC), either unsupervised or supervised with user input, followed by noise filtering. Second, subphase segmentation allowed further subdivision of phases and the generation of elemental density maps via kernel density estimation. These density maps were used to compute the Hydraulicity Index (HI) through ArcGIS map algebra. HI is commonly used by many authors to evaluate the hydraulicity degree of a mortar and, according to Boynton [8], it is defined by the following equation (1):

$$HI = \frac{SiO_2 + Al_2O_3 + Fe_2O_3}{CaO + MgO} \quad (1)$$

In addition, a grain size distribution study was carried out on the aggregates of the historical mortars to identify the dominant granulometric range, with special focus on the fine fraction. This fraction is crucial due to its increased specific reactive surface area, which can strongly influence the hydraulic reactivity of the mortars.

Fig. 2. Preparation of experimental mortars (left) and a representative specimen (right).

The analysis was performed using the Micro-Fabric Analyzer (MFA) [6], a novel GIS-based tool designed for the quantitative extraction of microstructural features from geomaterials. The MFA employs high-resolution RGB images from optical microscopy to accurately delineate individual grains and map their spatial distribution within thin sections. This GIS-based grain size analysis maintains the spatial context of the aggregates, allowing for a precise assessment of how particle size distribution and sorting correlate with hydraulicity maps obtained via Q-XRMA. By integrating these methods, the approach provides a deeper insight into the influence of microstructural features, particularly the fine aggregate fraction, on the physical and hydraulic performance of historical mortars.

III. RESULTS AND DISCUSSION

The results of all investigations provided valuable insights into the influence of aggregate composition and grain size distribution on the physical and mechanical performance of the examined lime mortars. In particular, for the experimental mortars, those made with ghiara aggregates containing the finer fraction (MG1) demonstrated better overall performance compared to those without it (MG2). Regarding capillary water absorption, the presence of the fine fraction in MG1 mortars led to greater packing density and consequently reduced open porosity. This is reflected in the lower capillary absorption coefficient. Conversely, MG2 mortars, which lack of the fine fraction, absorbed more water, indicating slightly higher water uptake. In the case of total immersion tests, the imbibition coefficient further confirmed this trend. Ghiara-based mortars with a fine fraction exhibited a slightly lower average imbibition coefficient than those without, again highlighting the compaction effect induced by the finer particles. For hardening times, assessed via the Vicat needle test, MG1 mortars began setting earlier and completed the process faster than MG2 mortars. The latter displayed a delayed onset of hardening, by approximately one hour, and a slower progression, suggesting a less reactive mix. In terms of compressive strength, the MG1 mortars also outperformed their MG2 counterparts. The inclusion of the fine fraction enhanced matrix compactness, which in turn resulted in improved resistance to mechanical stress. Perforation resistance tests confirmed these findings: ghiara-based mortars containing the fine fraction exhibited higher resistance values. Once again, the presence of finer aggregates contributed to an overall improvement of material strength and durability.

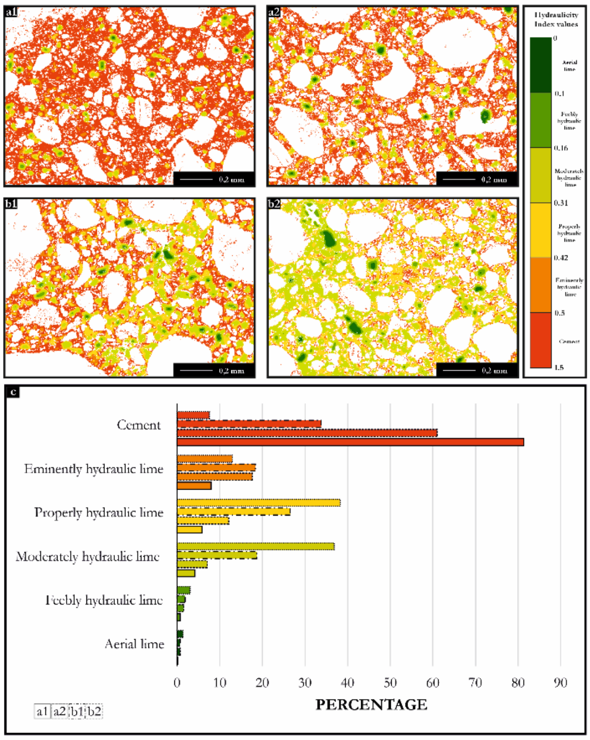

Fig. 3. Spatial distributions of the Hydraulicity Index (HI) within the binder, together with the corresponding abundance values, derived from Q-XRMA data for selected micro-domains of the experimental ghiara mortars (MG1 series above; MG2 series below).

To investigate whether factors beyond aggregate grain size affect the reactivity and, consequently, the hydraulic behavior of mortars, we conducted a comparative analysis that included historical samples. In this context, we used the Q-XRMA to identify and quantify the hydraulic phases within the binder of both experimental and historical mortars. Experimental ghiara-based mortars consistently exhibited high Hydraulicity Index (HI) values, typically ranging from 0.31 to 1.5, indicative of materials spanning from moderately hydraulic lime to cement-like behavior. In particular, mortars incorporating the fine fraction of ghiara (MG1) showed the highest HI values (Figure 3). In contrast, historical ghiara mortars displayed a broader variability in HI values depending on the sampling location. Indeed, some samples showed rather low HI values, falling within the range of feebly hydraulic lime, while others exhibited very high values. This heterogeneity can be interpreted as the cumulative outcome of multiple restoration interventions carried out over time, as well as the involvement of different craftsmen or production centers that may have employed raw materials with intrinsic variability and distinct preparation techniques. The chronological succession of mortar production itself could also have contributed to the observed heterogeneity. To further investigate the role of aggregate texture in the observed hydraulic variability, the Micro-Fabric Analyzer (MFA) was applied to optical microscopy images of historical mortars. This GIS-assisted tool enabled a detailed grain size analysis while preserving the spatial context of the aggregates within thin sections. The results showed that historical mortars, like their experimental counterparts with fine aggregates, generally exhibited a predominance of fine-grained components, suggesting potentially similar reactivity due to increased specific surface area. However, despite these comparable granulometric profiles, the hydraulic performance of historical mortars was not always aligned with that of the experimental MG1 formulations. This discrepancy indicates that other variables must be considered, such as the type and quality of lime used, as well as the provenance and mineralogical characteristics of the ghiara aggregate itself. For instance, variations in the glassy texture of the volcanic aggregate, linked to different quarrying sources, could significantly influence its pozzolanic reactivity. In summary, although aggregate grain size plays a key role in influencing mortar reactivity and hydraulic performance, the data obtained from the analysis of historical mortars suggest a more complex scenario, where multiple interrelated factors must be considered to fully understand the behavior of hydraulic lime mortars.

IV. CONCLUSION

This study investigated the role of aggregate properties, particularly grain size, in relation to the physical, mechanical, and hydraulic behavior of both experimental and historical lime mortars containing ghiara, a volcanic aggregate peculiar of the Etna territory. Through an integrated analytical approach combining traditional techniques (XRD, FTIR, polarized light microscopy) with innovative GIS-based image analysis tools (Q-XRMA and MFA), it was possible to gain a detailed understanding of the microstructural factors influencing mortar performance. Results from the experimental mortars showed that the inclusion of fine ghiara fractions significantly improves compactness, reduces water absorption, accelerates hardening times, and enhances mechanical strength. These effects are attributed to the increased specific surface area provided by the finer fraction, which promotes the formation of hydraulic phases and strengthens the binder–aggregate interaction. However, comparison with historical mortars revealed a more complex scenario, suggesting the influence of other key factors, such as the nature and provenance of the lime, the degree of vitrification of the ghiara, and the restoration practices applied over time. The combined use of Q-XRMA and MFA tools proved especially effective for spatially resolved assessments of aggregate distribution and binder reactivity, enabling in-depth comparisons between different mortar types. These methods also show great potential in the field of heritage science, not only for interpreting historical construction techniques but also for guiding the design of compatible and durable repair mortars. In this perspective, the integrated approach proposed offers valuable support in selecting compatible materials for conservation and restoration interventions on historical buildings.

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