Archaeometric investigation of archaeological materials and development of sustainable lime mortars with agro-wastes for the conservation of Cultural Heritage

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INTRODUCTION

The conservation of cultural heritage is a highly complex and continuously evolving field that does not merely involve defining the most appropriate intervention procedures but rather embraces as comprehensive a knowledge of the artefact as possible, paying attention also to those issues that are more specifically archaeometric in nature and that affect the object. Among archaeometric investigations, provenance studies of ancient stone materials, particularly white marbles, remain one of the most debated research fields due to their relevance for understanding ancient trade networks, workshop organization, artistic attribution and raw material procurement strategies (Attanasio et al., 2006; Antonelli & Lazzarini, 2015). Because white marbles from different quarry districts often display similar macroscopic characteristics, provenance determination generally requires the implementation of different methodologies drawn from geosciences, chemistry and the physical sciences.

Despite the archaeological importance of Calabria (southern Italy), archaeometric studies on marble artefacts from the region remain relatively scarce. Most previous investigations have focused on stone cargoes recovered from Roman shipwrecks along the Calabrian coasts, whereas studies concerning architectural and decorative contexts are still limited. Among the most significant archaeological sites in the region, the Roman Villa of Palazzi di Casignana preserves one of the largest mosaic complexes currently known in Calabria, although its decorative materials have only recently become the subject of archaeometric investigations.

In parallel, conservation science has increasingly embraced sustainability-oriented approaches, promoting the development of greener materials and practices with reduced environmental impact. Given the significant contribution of the construction sector to global carbon emissions, growing attention has been devoted to the valorization of agricultural and industrial by-products as alternative raw materials for mortar production, their application in lime-based mortars for cultural heritage conservation remains insufficiently explored. While green conservation research has largely focused on bio-based cleaning and consolidation systems, the development of repair mortars incorporating recycled waste materials deserves further investigation.

Within this framework, the present study combines archaeometric provenance research and sustainable conservation materials. The first part investigates the mineralogical and petrographic characteristics, as well as the provenance, of stone tesserae from the "A Grandi Fiori" mosaic in the Roman Villa of Palazzi di Casignana (Reggio Calabria, Italy). The second part evaluates the suitability of sustainable lime-based repair mortars incorporating olive stone powder and rice husk ash, assessing their physical, mechanical, and durability properties for potential applications in cultural heritage conservation.

METHODS

Archaeometric Investigation of the "A Grandi Fiori" mosaic tesserae

Stone *tesserae* from the *"A Grandi Fiori"* mosaic (3rd century CE) of the Roman Villa of Palazzi di Casignana (Reggio Calabria, Italy) were sampled during the conservation campaign carried out between 2020 and 2021. Following macroscopic examination, twenty-nine *tesserae* representative of the main lithotypes identified within the mosaic (24 white marble and 5 green limestone *tesserae*) were selected for archaeometric characterization and provenance studies.

A multi-analytical approach was adopted, as the provenance determination of white marbles cannot be reliably achieved through a single analytical technique. Samples were cleaned, powdered when necessary, and prepared as thin sections for petrographic investigation.

Minero-petrographic and micro-chemical characterization was performed through Polarized Optical Microscopy (POM), X-Ray Diffraction (XRD) and Scanning Electron Microscopy coupled with Energy-Dispersive Spectroscopy (SEM-EDS). Particular attention was devoted to the determination of maximum grain size (MGS),

Table 1 Mix design of the formulated POS and reference mortars. (v = parts by volume).

Specimen	Lime (g)	Sand (g)	POS (g)	Nanosilica/ POS ratio (w/w)	Water/ Binder ratio (w/w)	Flow (mm)
L	85.20	718.50	-	-	1.75	128
POS5L	85.20	680.96	13.31	-	2.21	128
POS10L	85.20	645.12	26.62	-	2.27	128
POS15L	85.20	609.28	39.94	-	2.30	128
POS5-SL	85.20	680.96	13.31	0.35	1.88	126
POS10-SL	85.20	645.12	26.62	0.35	1.88	127
POS15-SL	85.20	609.28	39.94	0.35	1.88	128

Boundary Grain Shape (GBS) of carbonate grains and the presence of directional geometric features (anisotropic texture), which represent key parameters for marble provenance studies (Lazzarini et al., 1980; Antonelli & Lazzarini, 2015). Provenance attribution of white marbles was further investigated through stable carbon and oxygen isotope analyses ($\delta^{13}C$ and $\delta^{18}O$) performed by mass spectrometry and compared with published isotopic databases.

Development of Sustainable Mortars Incorporating Powdered Olive Stone

A series of lime-based mortars was produced to evaluate the suitability of Powdered Olive Stone (POS), an agricultural by-product, as a sustainable aggregate replacement for conservation mortars. Mortars were formulated using hydrated lime (CL70-S), siliceous sand, POS, and, in selected mixtures, nanosilica. Three groups of mixtures were prepared: *i)* reference lime mortars, *ii)* mortars containing POS as partial sand replacement (5–15% by volume), and *iii)* mortars containing POS pre-treated with nanosilica under the same replacement ratios.

The binder-to-aggregate ratio was fixed at 1:3 by volume, following common conservation practice (Table 1). Water demand was determined through flow table testing (EN 1015-3:2001) to ensure comparable workability. Mortars were cast into standardized moulds and cured under controlled laboratory conditions (RH 60 ± 10%; 20 ± 5°C). Physical, microstructural, durability and mechanical properties were evaluated after 28 and 90 days through a comprehensive testing programme including colorimetric analyses (EN 15886:2010), optical microscopy, SEM observations, capillary water absorption (EN 15801:2010), ultrasonic pulse velocity (EN 14579:2005), bulk density determination (EN 772-13:2002), accelerated salt crystallization tests (EN 12370:1999) and compressive and flexural strength tests (EN 1015-11:2019).

Table 2 Mix design of the formulated RHA and reference mortars. Binder/aggregate ratio was fixed at 1:2 by volume for all formulations.

Specimen	NHL3.5 (g)	Lime (g)	RHA (g)	Binder (g)	Sand (g)	Water/ Binder ratio (w/w)	Flow (mm)
L	-	354.1	-	354.1	1983.0	1.33	133
NHL3.5	446.1	-	-	446.1	1983.0	1.00	130
RHA10L	-	318.6	35.5	354.1	1983.0	1.33	128
RHA20L	-	283.3	70.8	354.1	1983.0	1.33	133
RHA30L	-	247.8	106.3	354.1	1983.0	1.33	134
RHA50L	-	177	177	354.0	1983.0	1.33	133

Development of Sustainable Mortars Incorporating Rice Husk Ash

Rice husk was washed, dried, ground and calcined under controlled conditions at temperatures ranging from 500 to 800°C in order to produce rice husk ash (RHA). Different calcination temperatures were investigated to identify the most reactive pozzolanic material. The resulting ashes were characterized through SEM-EDS, X-Ray Fluorescence (XRF), XRD, Fourier Transform Infrared Spectroscopy (FT-IR), and Brunauer–Emmett–Teller (BET) specific surface area measurements.

The pozzolanic reactivity of the ashes was evaluated by preparing lime-RHA pastes and monitoring the evolution of hydration products and portlandite consumption through Thermogravimetric Analysis and Differential Scanning Calorimetry (TGA-DSC), supported by FT-IR and SEM-EDS observations. Similar approaches have been widely adopted for assessing the pozzolanic activity of siliceous waste materials and supplementary cementitious materials.

Based on the reactivity assessment, the most reactive ash was selected for mortar production. Lime-based mortars were prepared by partially replacing hydrated lime with RHA (10–50 wt.%), while reference mixtures based on hydrated lime and natural hydraulic lime (NHL 3.5) were also produced for comparison. Mortars were formulated using a binder-to-aggregate ratio of 1:2 by volume and water content was adjusted according to flow-table measurements (EN 1015-3:2001) (Table 2). Specimens were subjected to both standard and humid curing regimes. After curing, physical, microstructural, and mechanical properties were assessed through a series of standardized laboratory tests as described before. In addition to these tests, carbonation depth measurements (EN 14630:2006) were also performed.

RESULTS AND DISCUSSION

Archaeometric Investigation of the "A Grandi Fiori" mosaic tesserae

Petrographic, mineralogical and chemical analyses indicate that the green tesserae are biomicritic limestones characterized by an isotropic to slightly anisotropic texture and a micritic matrix containing planktonic foraminifera and radiolarians. According to the classifications of Folk (1962) and Dunham (1962), these lithotypes can be classified as biomicrites and mudstones. XRD analyses revealed a predominantly calcitic composition

with minor amounts of quartz and clay minerals, while SEM–EDS investigations identified iron-rich phases, including oxides and sulphides, likely responsible for the characteristic green coloration. Calcium oxalates (whewellite) were also detected and are probably related either to biodeterioration processes or to previous conservation treatments.

The overall petrographic and mineralogical features closely resemble those of the greenish-grey levels of the Variegated Clays Formation, extensively outcropping in the Casignana area (Critelli et al., 2016), although further investigations are required.

Petrographic observations allowed the subdivision of the white *tesserae* into three main groups according to maximum grain size (MGS), microstructural characteristics and mineralogical composition. Most samples consist of medium-grained marbles (MGS 1.45–3.25 mm), whereas a second group comprises fine-grained marbles (MGS 0.84–1.36 mm). A single specimen was identified as coarse-grained marble (MGS 6.90 mm).

The medium-grained marbles are generally characterized by heteroblastic fabrics, mortar-like microstructures, abundant deformation features and predominantly calcitic compositions, occasionally associated with minor dolomite and accessory phases. Fine-grained marbles exhibit mainly mosaic microstructures, variable degrees of deformation, and predominantly calcitic mineralogy.

Because of the extensive overlap of MGS values among Mediterranean quarry districts, petrographic observations alone were insufficient to determine provenance. Consequently, stable isotope analyses ($\delta^{13}C$ and $\delta^{18}O$) (Fig. 1), combined with mineralogical and SEM–EDS data, were used to refine provenance attribution.

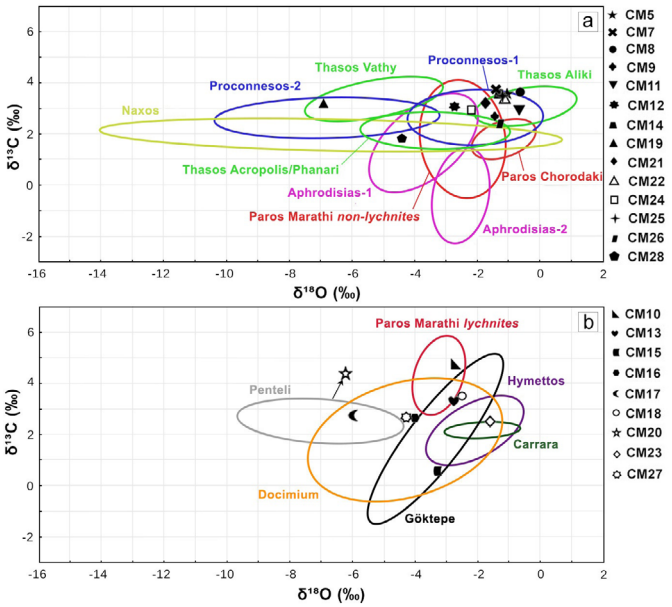

Figure 1 *Isotopic signatures of the white marble samples, plotted against ancient* ***a)*** *average- to coarse-grained marbles and* ***b)*** *fine-grained marbles fields. Modified from Attanasio et al. (2006), Attanasio et al. (2008), Musso et al. (2018), Prochaska & Attanasio (2021), Prochaska & Attanasio (2022), Prochaska (2023), Maniatis et al. (2024).*

The integration of petrographic, isotopic and mineralogical evidence revealed that the mosaic was produced using marbles from multiple quarrying districts rather than a single source.

The majority of the *tesserae* were attributed to the Proconnesian quarries of Marmara Island. Samples CM5, CM6, CM7, CM8, CM9, CM11, CM14, CM19, CM21, CM22, CM24, CM25, and CM26 display isotopic signatures, textural features, and accessory mineral assemblages consistent with the Proconnesos-1 and, in one case, Proconnesos-2 quarry districts. Petrographic features and minerals such as margarite, phlogopite, paragonite, Ti-oxides, and Fe-oxides provided decisive evidence for excluding alternative sources such as Thasos, Paros, and Aphrodisias.

Several tesserae were attributed to the Docimium quarries. Samples CM13, CM15, CM16, CM17, CM18, and CM27 display isotopic signatures and petrographic characteristics fully compatible with this Anatolian source. In particular, sample CM27 falls exclusively within the Docimium isotopic field, while the remaining samples exhibit combined petrographic and geochemical features that allow the exclusion of competing sources such as Göktepe and Parian *lychnites*.

Sample CM23 was attributed to Carrara marble. Although isotopic data are compatible with both Carrara and Docimium, the polygonal microstructure characterized by straight grain boundaries and abundant 120° triple junctions strongly support a Carrara provenance.

Sample CM20 was identified as Pentelic marble. Its isotopic composition falls within the recently revised isotopic field of the Pentelicon quarries, while the marked schistosity, quartz-rich assemblage, and abundant mica content provide further confirmation of this attribution.

The coarse-grained sample CM28 was unequivocally assigned to the Naxos quarry district. Both MGS values and isotopic composition are fully consistent with Naxian marble, while the observed heteroblastic texture and strained calcite crystals correspond closely to the diagnostic petrographic characteristics described in the literature.

A particularly interesting case is represented by sample CM10. Although its MGS would traditionally place it among medium-grained marbles, isotopic data suggest affinity with Parian *lychnites*. However, the occurrence of significant dolomite contents contradicts this interpretation. The combined petrographic, mineralogical, and isotopic evidence instead points toward a possible provenance from the Ephesian marble district. Nevertheless, because the distribution of Ephesian marble within the Roman Empire remains poorly documented, this attribution should be regarded as tentative.

The archaeometric investigation demonstrates that the "A Grandi Fiori" mosaic was produced using marbles originating from different regions of the Roman Empire,

including Asia Minor, Greece and Italy. The predominance of Proconnesian marble is particularly noteworthy. During the 3rd century CE, Proconnesian quarries became one of the principal suppliers of architectural marble throughout the Empire, progressively replacing Carrara in many public building projects (Attanasio et al., 2008).

The occurrence of smaller quantities of Docimian, Pentelic, Carrara, Naxian and possibly Ephesian marbles raises interesting questions concerning procurement strategies. Given their limited representation, the reuse of pre-existing architectural elements cannot be excluded. The extensive modifications documented in the Villa of Casignana during the 3rd century CE provide a plausible context for the reworking and reuse of earlier decorative materials. Further archaeometric investigations on additional architectural elements from the villa will be necessary to clarify the relative importance of primary procurement and material reuse within the broader decorative programme of the site.

Development of Sustainable Mortars Incorporating Powdered Olive Stone

Macroscopic observations and colorimetric measurements consistently demonstrated that the incorporation of powdered olive stone (POS) significantly affected the chromatic appearance of the mortars. Increasing POS contents produced progressively darker and more yellowish surfaces, reflecting the intrinsic colour of the lignocellulosic particles embedded within the matrix. This trend was confirmed by the negative ΔL* values and the positive Δa* and Δb* coordinates recorded for all formulations relative to the reference mortar (Fig. 2).

The chromatic alteration became more pronounced as the replacement level increased from 5% to 15%, indicating a direct relationship between POS content and colour modification. The addition of nanosilica partially mitigated these effects, particularly at lower POS dosages, resulting in smaller total colour differences (ΔE) compared with the corresponding POS-only mortars.

Nevertheless, colour compatibility remains a critical requirement in conservation practice and should always be evaluated against the original historic substrate through preliminary diagnostic investigations and colour-matching procedures.

Capillary water absorption tests revealed significant modifications in the hydric behaviour of the mortars following POS incorporation.

During the initial stages of the test, reference mortars displayed the highest absorption rate, whereas POS-containing specimens absorbed water more slowly. This behaviour became increasingly evident with higher replacement levels and can be attributed to modifications in pore size distribution. The lower sorptivity observed in POS mortars is consistent with the development of larger capillary pores, whose reduced capillary pressure limits the initial water uptake.

At longer exposure times, however, the trend reversed. Mortars containing POS ultimately absorbed larger quantities of water than the reference specimens, indicating a substantial increase in total open porosity. This effect was particularly evident in formulations with higher POS contents. The absorption curves of POSL and POS-SL mortars displayed two distinct slopes, suggesting a bimodal pore network.

The increased porosity can be attributed to two concurrent mechanisms. First, the higher water demand required by POS-containing mixtures promotes the formation of larger capillary voids during curing, as previously reported for lime mortars . Second, the intrinsic porous structure of olive stone particles contributes additional internal porosity capable of storing water.

The incorporation of nanosilica partially counteracted this behaviour. POS-SL mortars generally exhibited lower water absorption than the corresponding POSL specimens, indicating a densification of the binder matrix likely associated with pozzolanic reactions and the formation of calcium silicate hydrate (C–S–H) phases.

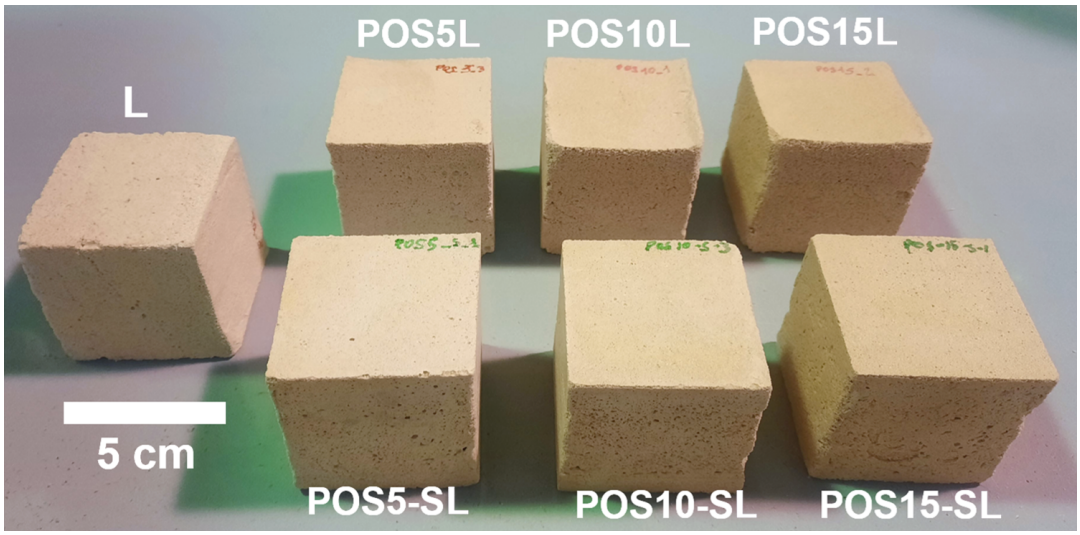

Figure 2 *Macroscopic appearance of the formulated mortars.*

The durability assessment through accelerated salt crystallization tests further highlighted the influence of microstructural modifications induced by POS and nanosilica. During the first seven cycles, all mortars experienced mass increases due to salt accumulation within the pore network. The highest mass gains were recorded for mortars containing elevated POS percentages, particularly POS15L, reflecting their greater porosity and capacity for salt uptake (Fig. 3).

After the 8th cycle, however, deterioration processes became dominant. Progressive cracking, exfoliation and material loss were observed in all experimental mortars. POS-based specimens showed greater salt accumulation but also experienced severe degradation and eventual disintegration. Mortars with higher POS contents failed earlier, indicating that the enhanced porosity facilitated salt ingress and crystallization, thereby accelerating internal damage.

Interestingly, nanosilica-modified mortars exhibited lower initial salt uptake and delayed deterioration during the early stages of testing. Nevertheless, once damage initiated, degradation progressed rapidly and all POS-SL formulations failed before completion of the test. This behaviour may be attributed to the development of higher crystallization pressures in the finer pore network.

Overall, the reference mortars demonstrated the highest durability, surviving all crystallization cycles. POS increased porosity and potentially enhanced sacrificial behaviour by accommodating salts within the repair mortar rather than the original substrate.

Bulk density measurements confirmed the substantial influence of POS on mortar structure. Reference specimens exhibited average values around 1.64 g/cm^3, consistent with previous studies on traditional lime mortars. The replacement of siliceous aggregate with POS progressively reduced density, reaching minimum values in POS15 mortars. This decrease reflects the significantly lower density of olive stone particles compared with quartz aggregates.

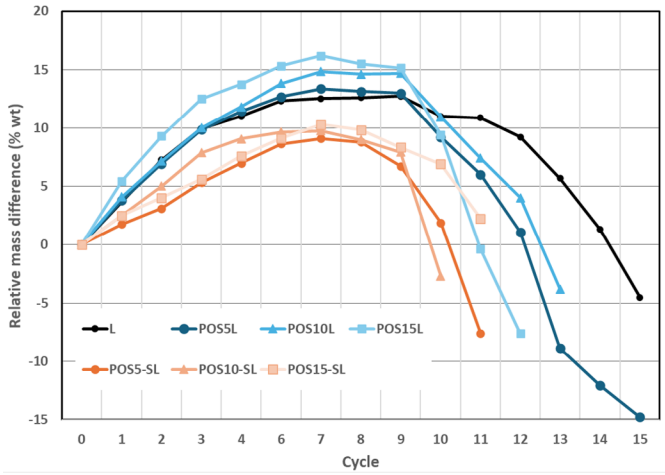

Figure 3 Curve representing the weight variation of olive-stone and reference mortars during the salt crystallization cycles.

Conversely, nanosilica partially restored density values, suggesting a denser and more compact binder matrix. SEM-EDS investigations provided direct evidence supporting this interpretation. Olive stone particles displayed a highly porous cellular microstructure characterized by lumens and cracks, confirming their contribution to the increased porosity observed during water absorption testing.

Microchemical analyses of the binder matrix indicated substantial differences between formulations. Reference and POS mortars were characterized by high CaO contents and relatively limited silica concentrations, in contrast, nanosilica-modified mortars exhibited significantly higher SiO_2 concentrations consistent with the formation of C-S-H phases. The presence of these reaction products at the binder–aggregate interface confirms the occurrence of pozzolanic reactions and explains the observed matrix densification.

Despite these microstructural improvements, mechanical testing revealed a progressive decrease in strength with increasing POS content (Fig. 4).

Reference mortars exhibited the highest flexural and compressive strengths, whereas POS-containing specimens showed lower values, particularly at replacement levels above 10%. The reduction can be attributed to the increased porosity and lower mechanical resistance of the organic particles compared with quartz aggregates.

Unexpectedly, the incorporation of nanosilica did not improve mechanical performance. Instead, POS-SL mortars displayed even lower flexural and compressive

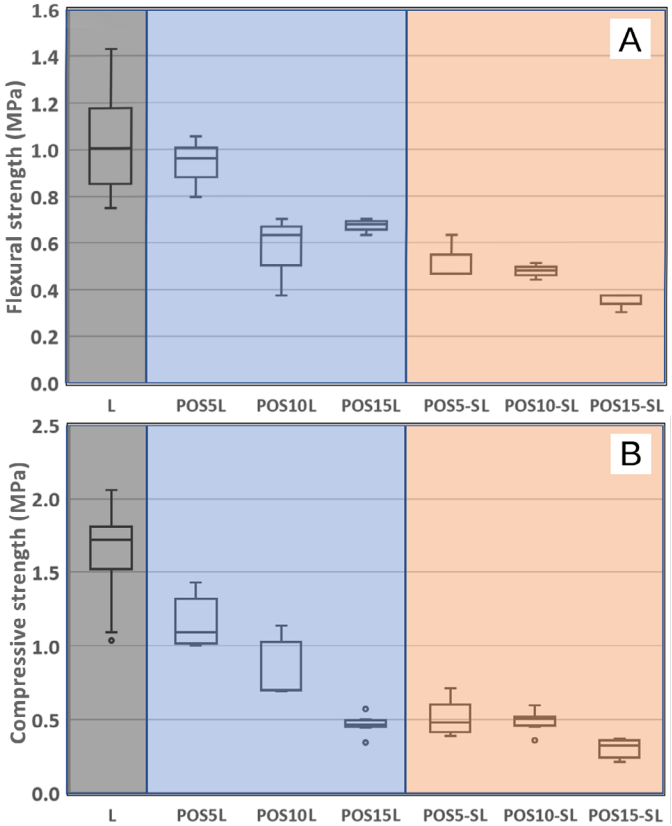

Figure 4 Flexural ***a)*** and compressive ***b)*** strength of reference and POS mortars specimens.

strengths than the corresponding POS formulations. Ultrasonic Pulse Velocity (UPV) measurements corroborated these results, showing a progressive decrease in wave propagation velocity from the reference mortars to the POS and POS-SL series, indicating reduced compactness and structural continuity.

Although nanosilica is generally recognized for enhancing strength through filler and pozzolanic effect, its effectiveness appears to have been limited by the characteristics of the POS particles. The highly porous structure of the olive stone aggregates likely weakened the interfacial transition zone (ITZ), reducing the ability of newly formed C–S–H phases to effectively reinforce the matrix. Similar behaviour has been reported in mortars containing recycled aggregates, where aggregate defects compromise the beneficial effects of supplementary cementitious materials.

Another explanation can be found in the occurrence of particle aggregation in the presence of nanosilica. To further investigate this phenomenon, image analysis was performed on optical micrographs of POS15L and POS15-SL mortars. Quantitative measurements revealed statistically significant differences in particle size distribution. While both formulations were dominated by fine particles, the nanosilica-treated mortars exhibited larger apparent particle areas and a broader size distribution. The formation of larger agglomerates likely reduced the homogeneity of the mortar matrix and generated local stress concentration zones. Such aggregation phenomena are well documented in nano-modified cementitious systems and may negatively affect mechanical performance by weakening internal bonds and disrupting stress transfer mechanisms.

Development of Sustainable Mortars Incorporating Rice Husk Ash

The characterization of rice husk ashes (RHAs) produced at different calcination temperatures demonstrated that thermal treatment strongly influences their morphology, mineralogy, and pozzolanic reactivity. SEM observations revealed that ashes calcined between 500 and 700°C retained the characteristic multilayered microstructure of rice husks, whereas calcination at 800°C induced significant sintering phenomena, resulting in structural collapse and the formation of a denser, partially vitrified surface. These morphological changes were reflected in the specific surface area values obtained by BET analysis.

Chemical analyses showed that all ashes were predominantly composed of silica (> 87 wt.%), with minor quantities of Al_2O_3 and K_2O and other trace elements. The combined content of SiO_2, Al_2O_3, and Fe_2O_3 exceeded 91 wt.% in all samples, satisfying the requirements for highly reactive pozzolanic materials. Loss-on-ignition values decreased progressively with increasing calcination temperature, indicating more complete oxidation of organic matter at higher temperatures.

Mineralogical investigations revealed that RHAs produced at 500–700°C consisted mainly of amorphous silica, characterized by broad diffuse XRD halos centered around 21.8° 2θ. Conversely, RHA800 exhibited crystalline silica phases, including cristobalite and tridymite, confirmed by both XRD and FT-IR analyses. These findings suggested that lower calcination temperatures favor pozzolanic activity.

The reactivity of the ashes was further evaluated through lime-paste experiments. SEM analyses identified widespread honeycomb-like calcium silicate hydrate (C–S–H) phases in all mixtures after 28 days of curing, confirming the occurrence of pozzolanic reactions. TGA/DSC analyses demonstrated progressive portlandite consumption over time, with RHA500 showing the highest reactivity and complete lime consumption within 14 days. RHA600 and RHA700 exhibited similarly high reactivity, while RHA800 showed substantially lower performance, consuming only 85% of the available portlandite after 28 days. FT-IR analyses corroborated these findings through the development of characteristic C–S–H absorption bands at around 966 cm^{-1}. The superior performance of RHA500 was attributed to its large specific surface area and predominantly amorphous silica content. Consequently, RHA500 was selected for mortar production.

The incorporation of RHA500 significantly affected the visual appearance of lime mortars (Fig. 5).

Colorimetric measurements revealed a progressive decrease in lightness (L*) as the percentage of RHA increased, resulting in darker mortars. This darkening effect represented the primary contributor to the overall colour difference (ΔE), whereas variations in the red-green (a*) and yellow-blue (b*) coordinates remained negligible. The observed darkening was attributed to the intrinsic grey colour of the ash and the presence of residual carbon originating from combustion.

Capillary absorption tests demonstrated that all RHA mortars absorbed more water than the reference hydrated lime mortars. The increased water absorption was attributed primarily to the highly porous structure of RHA particles, which can retain significant amounts of water. Nevertheless, no direct proportionality between

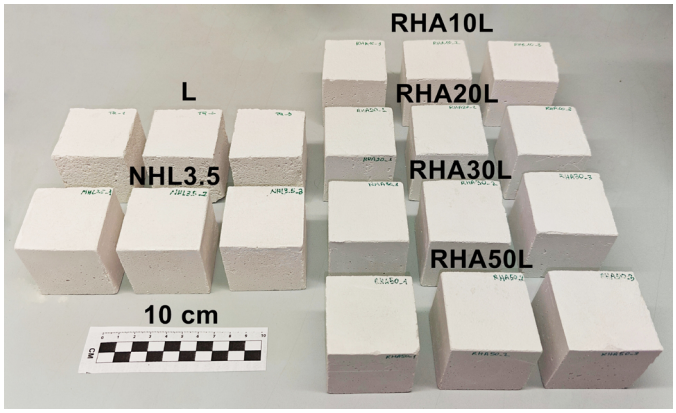

Figure 5 *Image of the macroscopic aspect of the formulated mortars.*

RHA dosage and water uptake was observed. This behavior suggests the coexistence of two competing mechanisms: increased porosity associated with RHA particles and pore refinement resulting from the formation of C-S-H phases. The latter effect appeared particularly evident under humid curing conditions, where pozzolanic reactions were enhanced and absorption coefficients generally decreased.

Interestingly, the capillary behavior of RHA mortars closely resembled that of NHL 3.5 mortars, which are widely used in conservation practice. This similarity suggests that RHA-based mortars may represent a viable and more sustainable alternative to traditional hydraulic lime formulations.

Salt crystallization tests highlighted the influence of both RHA content and curing conditions on durability. Compared with reference lime mortars, RHA and NHL mortars exhibited greater initial mass increases due to higher salt uptake. Under standard curing conditions, RHA mortars progressively accumulated salts before undergoing severe deterioration characterized by cracking, crumbling and eventual failure between the 9th and 11th crystallization cycles. NHL mortars exhibited slightly better durability, surviving until the 14th cycle.

Mortars cured under high humidity experienced more rapid degradation. Enhanced pozzolanic reactions promoted the development of finer pore networks, which increased crystallization pressures and accelerated failure. Despite this limitation, the overall durability of RHA mortars remained comparable to that of NHL-based formulations, supporting their potential applicability in conservation interventions.

Mechanical testing revealed contrasting effects on flexural and compressive strength. Flexural strength decreased significantly with RHA incorporation, remaining substantially lower than both hydrated lime and NHL mortars. However, humid curing improved flexural performance compared with standard curing.

Compressive strength exhibited a different trend. While 10% RHA replacement reduced strength, higher replacement levels increased compressive performance, with RHA30L mixtures achieving the highest values. This improvement was attributed to the formation of C–S–H phases generated through pozzolanic reactions. Overall, except for RHA10L, compressive strengths were comparable to or slightly higher than those of NHL mortars, indicating satisfactory compatibility with conservation requirements.

Carbonation tests showed that RHA mortars exhibited greater carbonation depths than reference lime mortars, with carbonation increasing progressively as RHA content increased. The highest replacement level (50%) produced the deepest carbonation fronts and, under standard curing, complete consumption of portlandite. Under humid conditions, carbonation was less pronounced, and the reduction in alkalinity was mainly associated with pozzolanic reactions. These findings confirm that RHA promotes lime consumption and accelerates the development of hydraulic phases, particularly at higher substitution levels.

CONCLUSIONS

This research provided a dual contribution to the fields of archaeometry and cultural heritage conservation.

The archaeometric investigation concerned the "A Grandi Fiori" mosaic (3rd century CE) from the Roman Villa of Palazzi di Casignana (Southern Italy). Twenty-nine *tesserae* samples, including green limestone and white marble specimens, were analyzed through a multi-analytical approach. Results suggest that the green *tesserae* were biomicritic limestones, likely associated with the Variegated Clays Formation near Casignana. Provenance analyses of the white marble *tesserae* revealed a predominance of Proconnesian marble, accompanied by smaller contributions from Anatolian, Greek and Italian sources. These findings are consistent with established trade networks and material circulation patterns of Late Antiquity and provide valuable insights into ancient procurement strategies, reuse practices, and artisanal production technologies.

The second part of the research investigated the use of powdered olive stone (POS) and rice husk ash (RHA) as sustainable additives in conservation mortars. POS was employed as a partial replacement for quartz aggregates, while RHA was used as a substitute for hydrated lime.

POS incorporation increased porosity and water absorption, potentially enhancing the sacrificial behavior of repair mortars exposed to salt weathering. Although nano-silica addition reduced water uptake through matrix densification, it did not significantly improve mechanical performance. RHA characterization demonstrated that ashes calcined at 500°C exhibited the highest pozzolanic reactivity due to their amorphous silica content and high specific surface area. Overall, mortars containing RHA500 showed capillary absorption, salt-crystallization resistance and mechanical performance comparable to natural hydraulic lime mortars.

In conclusion, the results demonstrate that agricultural waste-derived materials can successfully be incorporated into conservation mortars, contributing to both environmental sustainability and the development of compatible repair materials for historic built heritage.

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