Ancient building practices in the Phlegraean Fields: material characterisation of the Tempio di Apollo (Italy)

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ABSTRACT

This study investigates the building materials and techniques used in the Tempio di Apollo, located in the Phlegraean Fields (southern Italy), an area of active volcanoes with caldera-forming eruptions in the past and also characterised by present-day bradyseism. The availability of pyroclastic deposits strongly addressed the local building practices. Mortar and brick samples were collected from selected structural sectors of the monument, adopting a minimally invasive sampling approach. Analytical investigations were carried out through Polarized Light Microscopy (PLM), X-ray Powder Diffraction (XRPD), and Scanning Electron Microscopy (SEM).
The mortars are lime-based and show variable degrees of cohesion. The binder appears micritic to cryptocrystalline, with frequent lime lumps. The aggregates are mainly composed of volcanic fragments such as pumice, with occasional ceramic fragments. XRPD data confirm calcite as the dominant binder phase, reflecting the original choices in raw material; the presence of gypsum and halite reflect subsequent alteration processes. These results underline the deliberate use of local volcanic products and illustrate the technological strategies adopted by Roman builders to ensure durability and structural performance. The study contributes to a broader understanding of ancient construction practices in dynamic volcanic landscapes.

KEYWORDS: Roman mortars, hydraulicity, ceramic.

INTRODUCTION

The durability of Roman constructions continues to be studied in the geologic, archaeometric and material field, particularly due to the ability of such constructions to withstand the effects of time and environmental agents (Columbu et al., 2015; Di Benedetto et al., 2018; Rispoli et al., 2020). Mortars represent a category of geomaterials with significant scientific interest, as they allow investigation into technological, functional, and cultural aspects of ancient building practices (Oleson & Jackson, 2014). Their analysis integrates geological, chemical, and archaeological expertise, providing a multidisciplinary perspective that can contribute to the understanding of ancient technologies, the provenance of raw materials (Columbu, 2017), the chronological construction phases (Ramacciotti et al., 2018) and offer scientific support for conservation interventions (Columbu et al., 2018; Montesano et al., 2022; Rispoli et al., 2025).

Among the most important contexts for studying ancient mortars, the Phlegraean area stands out as a natural geological and archaeological laboratory. Within this geological and cultural landscape, Roman architects and craftsmen developed construction techniques capable of exploiting the mechanical, hydraulic and thermal properties of locally available volcanic products (Amalfitano et al., 1990; Oleson & Jackson, 2014, Cairoli, 2018). The architectural complex known today as the so-called Tempio di Apollo, located near Lake Avernus, represents a significant example of this technological tradition (De Jorio, 1822).

Despite its traditional designation as a temple, historical and archaeological research indicates that the building served as part of an extensive bath complex, built during the 1st century AD to exploit some hydrothermal springs identified along the eastern side of Lake Avernus. In the 2nd century AD the large octagonal hall (*frigidarium*) visible today (Da Eboli, 1494; Pagano 1984; Amalfitano et al., 1990) was built. The building is characterised by an intricated construction history and using different masonry techniques, including *opus caementicium* and *opus testaceum* (Di Luca, 2018), combined with a wide variety of geomaterials. However, a systematic characterisation of the mortars and bricks, which are the structural elements of the building, has not yet been carried out. This represents a critical gap in the understanding of construction choices, repair strategies, and material transformations over time in a volcanic environment strongly influenced by weathering, bradyseism, and anthropic interventions.

This study aims to investigate the mineralogical and petrographic features of bedding mortars and bricks from selected sectors of the so-called Tempio di Apollo, following a minimally invasive sampling strategy. A multi-analytical approach was adopted, combining Polarised Light Microscopy (PLM), X-ray Powder Diffraction (XRPD), and Scanning Electron Microscopy (SEM) to define the composition, texture, and alteration patterns of mortars. Particular attention is given to the origin of raw materials, the role of volcanic components in giving hydraulic properties, and the occurrence of neo-formed phases linked to post-laying processes.

The use of local materials, the interaction between binders and volcanic aggregates, and the possible formation of secondary phases are elements of considerable interest for construction materials and for understanding the technical strategies of the ancient Romans to ensure the resilience of constructions (Rispoli et al., 2016).

The results provide new insights into the preparation of construction materials in the Phlegraean context and contribute to the reconstruction of Roman building practices in a region where the interaction between human activity and an evolving volcanic landscape has been continuous from antiquity to the present (Dilaria et al., 2024; Rispoli et al., 2025).

GEOLOGICAL AND ARCHAEOLOGICAL BACKGROUND

The Tempio di Apollo is located in Pozzuoli (near Averno Lake), in the Phlegraean Fields Area (West Naples, Italy), which constitutes the largest volcanic system of Southern Italy, and which formed through a sequence of caldera-forming eruptions (Fedele & Morra, 2011). Together with the Somma-Vesuvius volcanic system, the Phlegraean Fields are located in the central part of the Campanian Plain, structurally representing a zone of tectonic subsidence. The origin of the Campanian Plain is linked to extensional tectonic processes that have affected the Tyrrhenian region since the Plio-Pleistocene, as a result of complex geodynamic events in the Western Mediterranean that led to the opening of the Tyrrhenian basin and the development of the Apennine-Maghreb chain (Rolandi et al., 2003; D'Argenio et al., 2012; Ciarcia et al., 2013; Vitale & Ciarcia, 2018). These extensional tectonics caused the Apennines to subside toward the central Tyrrhenian, resulting in the sinking of the western margin and fuelling intense volcanic activity - including at Roccamonfina, Phlegraean Fields, and Somma-Vesuvius - as well as the formation of large depressions, such as the Campanian Plain and the Sele Plain, which were subsequently filled with volcanoclastic and alluvial sediments (Ciarcia et al., 2013). Volcanic activity in the Phlegraean Fields is marked by the production of large volumes of pyroclastic deposits, predominantly from explosive eruptions, with occasional effusive events represented by lava flows and domes. The volcanic products of the Phlegraean Fields are characterised by a potassium-alkaline affinity, typical of the Roman Magmatic Province (Fedele & Morra, 2011). The two most significant eruptive events occurred around 39.000 years ago (Ricci, 2000; De Vivo et al., 2001) - the Campanian Ignimbrite eruption, the most catastrophic explosive event in the Mediterranean over the last 200.000 years - and approximately 15.000 years ago (Deino et al., 2004; Colella et al., 2013), marked by the eruption of the Neapolitan Yellow Tuff, the most substantial event in the Phlegraean Fields in terms of thickness and areal extent. Phlegraean Fields activity continues nowadays and is evidenced by recent activity such as the Monte Nuovo eruption (adjacent to the site under investigation) in 1538 (Piochi et al., 2005), fumaroles, and the phenomenon of bradyseism, which has led to Pozzuoli being popularly referred to as the "dancing land" (local toponymy due to ground movements).

A product of the ingenuity of the ancient Romans, the so-called Tempio di Apollo enhances the natural setting of the Lake Avernus, where it is located. The edifice is set on the eastern side of the Avernus crater (Amalfitano et al., 1990). Its name derives from the oracle of the god Apollo, associated with the *Cumaean* Sibyl and the identification of the lake as the gateway to the underworld. Since ancient times, it has been well known that the structure was used for non-religious purposes, specifically thermal baths, making the name attributed to it somewhat inaccurate (De Jorio, 1822). A rare medieval manuscript testifies about the thermal waters of the Phlegraean Fields (Da Eboli, 1494) recounts the presence of two thermal baths located respectively to the left and right of the site, called *Balneum Succellarium* and *Balneum De Ferris*, confirming that the area was fed by springs that made the therapeutic and recreational use of the waters possible. The Tempio di Apollo is divided into several sections arranged around the main hall, has an octagonal plan externally and a circular one internally (Fig. 1), with a dome roof - now destroyed - that was estimated to have a diameter of 38 metres, dimensions closely comparable to those of the Pantheon in Rome, indicating the importance the building must have had at the time (Amalfitano et al., 1990). Structurally, the building is arranged into an upper and a lower level. A series of arched windows surrounds the upper floor (Fig. 1, black arrows), while the lower floor features eight niches - four semicircular and four rectangular - one of which opens toward the lake (Fig. 1, white arrows; (Amalfitano et al., 1990). This type of architecture immediately invites comparison with the nearby archaeological complex of the Baiae Thermal Baths, particularly the Temple of Venus (Rispoli et al., 2025). The complex covers 120 metres total length, extending to the south and north of the central domed hall.

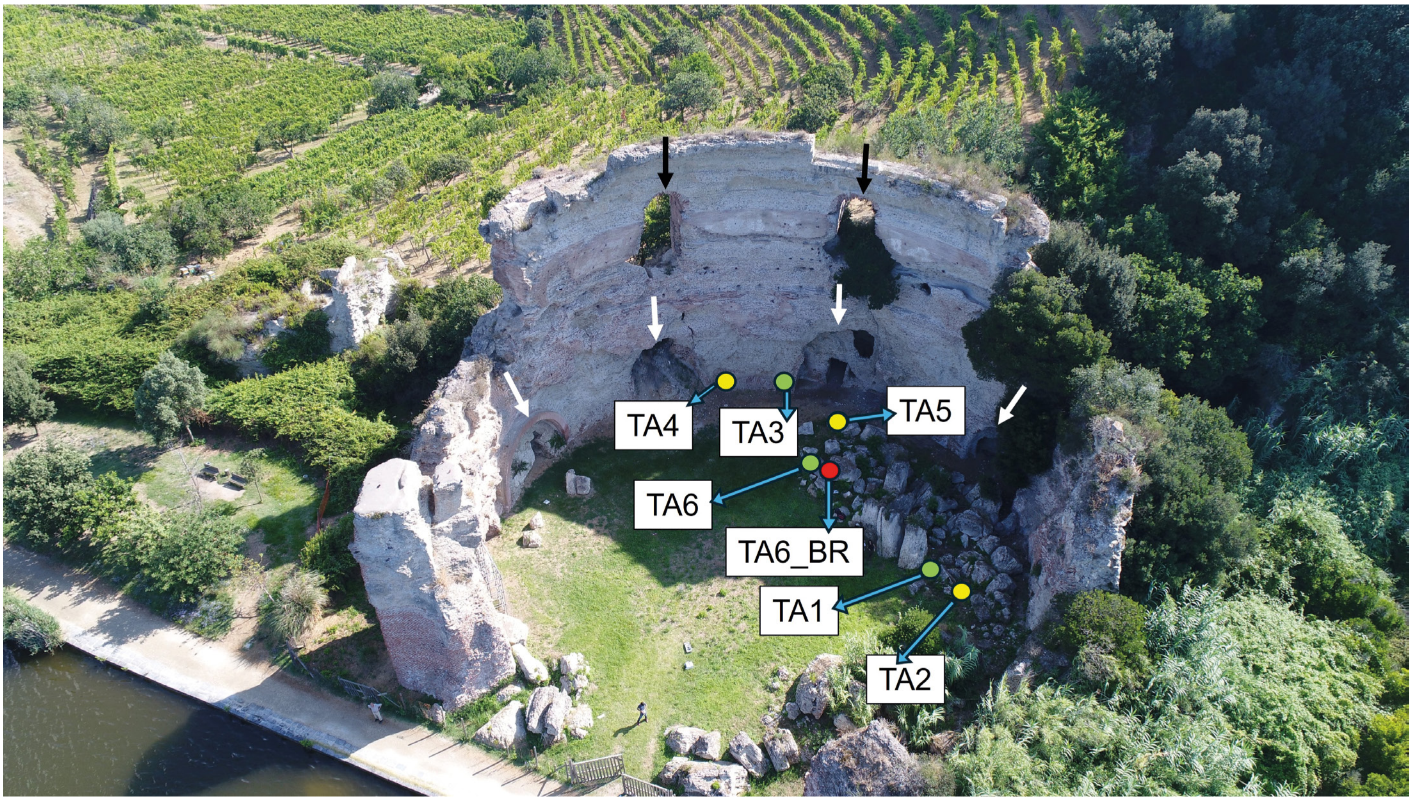

Fig. 1 - Aerial photograph of Tempio di Apollo with the location of the sampling points. Black arrows indicate arched windows surrounds the upper floor; white arrows indicate niches of the lower floor (see text for further details).

The interior facing of the central hall was covered with plaster, remnants of which still remain. Where the plaster has fallen away, *opus testaceum* and mortar can be seen (Fig. 1). The presence of *opus caementicium* in the lower part of the hall and *opus testaceum* in the rest of the dome indicates that the complex dates to the 1st century AD, with restorations in the 2nd century AD. This choice was likely driven by structural reasons, aiming to avoid overloading the walls and placing excessive stress on the foundations of the structure (Amalfitano et al., 1990).

MATERIALS AND METHODS

For this study, samples from the Tempio di Apollo were investigated (Fig. 2; Tab. 1). Sampling strategy and procedure were planned in collaboration with the Archaeological Park of the Phlegraean Fields. Prior to sampling, a detailed on-site inspection and a photographic survey were carried out to define suitable and representative sampling points (Fig. 1). Sampling was conducted only in areas where the removal of small fragments could be carried out without compromising the integrity and legibility of the architectural surfaces, while still ensuring the representativeness of the examined materials. It is worth noting that the mortars collected from ground level originally belonged to the upper portions of the structure.

A preliminary macroscopic approach was performed in order to make a first characterisation of the materials and to plan the investigations. Samples were then investigated through Polarised Light Microscopy (PLM), X-Ray Powder Diffraction (XRPD), and Scanning Electron Microscopy (SEM) performed at the Department of Earth, Environmental and Resource Sciences (DiSTAR) of University of Naples Federico II (Italy).

Petrographic investigations were carried out on rock thin sections using a LEITZ Laborlux 12 Leica POL polarizing microscope. Micro-textural observations were obtained through Field Emission Scanning Electron Microscopy (FESEM) Zeiss Merlin VP Compact, coupled to an X-ray energy dispersion spectrometer (EDS) and Oxford Instruments Microanalysis Unit (INCA X-stream pulse processor operating at 15-kV primary beam voltage, 50–100 A filament current, variable spot size, from 30,000 to 200,000× magnification, 20 mm working distance, and 10-s acquisition time) and INCA Energy software 5.05 (XPP array and pulse pile-up corrections) for data acquisition. The quant optimisation was carried out using cobalt (FWHM–full width at half maximum peak height- of the strobed zero = 60–65 eV). For details on corrections and standards, refer to Guarino et al. (2021), for precision and accuracy to Rispoli et al. (2019). Volume percentage estimation was determined according to Terry & Chilingar (1955) comparative charts.

Qualitative X-Ray Powder Diffraction phase analyses (XRPD) were performed on powders with grain size < 10 µm obtained by using a McCrone micronizing mill, (agate cylinders and wet grinding time of 15 min; Retsch-Alle, Haan, Germany) through a Malvern Panalytical X'Pert Pro diffractometer equipped with a RTMS X'Celerator. Malvern Panalytical High Score Plus 3.0 software was used for phase identification, along with PDF-2 and ICSD database (International Crystal Structure Database-ICSD, 2012). Operating

Table 1 - List of the examined samples from the Tempio di Apollo with location of sampling points (see also Fig. 1 and 2).

Sample	Type	Colour*	Aggregate size	Cohesion**	Location
TA1	bedding mortar +tuff	beige	up to 1 cm	+++	ground
TA2	bedding mortar	beige	up to 0.3 cm	+++	ground
TA3	bedding mortar+tuff	light yellow	up 0.8 cm	++	wall
TA4	bedding mortar	dark reddish brown	up to 1.5 cm	++	wall
TA5	bedding mortar	light beige	up to 0.8 cm	+++	ground
TA6	bedding mortar+brick	yellow+ dark reddish brown	up 0.7 cm	++	ground
TA6_BR	brick	dark red			ground

* colour: for mortar samples, colour refers to the binder;
**cohesion has been evaluated to the touch, depending on the crumbling of the material: +++ high; ++ medium.

Fig. 2 - Macroscopic photograph of the examined samples.

conditions were: CuKα radiation, 40 kV, 40 mA, 2θ range from 4 to 70°2θ, equivalent step size 0.017 °2θ, equivalent counting time 120 sec per step.

RESULTS

Texture and Polarised Light Microscopy (PLM)

Macroscopic observations revealed a high similarity among all the samples of the bedding mortars from the ground (Tab. 1; Fig. 2) as they display a high degree of cohesion, a light beige-to-beige colour and an aggregate size up to 1 cm. On the contrary, the two samples of the bedding mortars from the wall display lower cohesion and a colour varying from light yellow to dark- reddish brown and an aggregate size of 0.8 and 1.5 cm respectively. Aggregates are represented by volcanic and ceramic fragments. Pumice fragments may show evidence of recarbonation, meaning that when mixed with lime and water, they are integrated into the mortar and participate in lime's carbonation process, assuming partially or completely the textural features of the surrounding carbonatic matrix. Lime lumps, which represent non-reacted lime (i.e., lime poorly slaked during the preparation of the mortar which then carbonated separately from the rest of the binder matrix; Montesano et al., 2022; Rispoli et al., 2025) are also visible.

TA1

The TA1 bedding mortar is in contact with the tuff; the tuff is characterised by crystal and glass fragments embedded in an altered cineritic matrix. The indistinct boundary between mortar and tuff reflects a strong interaction between the materials.

The binder fraction is characterised by a micritic matrix (Fig. 3a) and the presence of rounded lime lumps (Fig. 3b). The aggregate fractions (about 40% of the mortar) is predominantly of volcanic origin and mainly represented by pumice fragments with evidence of recarbonation (Fig. 3a). Crystal fragments of alkali feldspar and mica are also observed (e.g., Fig. 3c-d). Sporadic ceramic fragments are also embedded within the matrix of the mortar (Fig. 3c-d), exhibiting inactive optical activity of the ceramic body including mica and alkali feldspar.

TA2

The TA2 bedding mortar shows a binder with a prevailing cryptocrystalline matrix (Fig. 3e-f) containing subrounded lime lumps. The aggregate fraction represents about the 40% of the mortar and is mainly represented by volcanic fragments (pumice) with evident recarbonation, displaying well-defined reaction rims (Fig. 3e).

TA3

Sample TA3 includes a tuffaceous portion, likely a remnant of a large block or wide aggregate, visible along the edges of the thin section (Fig. 4a-b), which is characterised by a cineritic matrix containing crystal and glass fragments. The binder fraction consists of a roughly equal proportion of micritic and cryptocrystalline matrix, along with the presence of rounded lime lumps (Fig. 4a-b). Additionally, gypsum has been also detected (Fig.4c-d). Aggregates make up approximately 30% of the mortar and are primarily composed of pumice fragments, mostly altered for recarbonation processes. In pozzolanic mortars a part of the $Ca(OH)_2$ is consumed by pozzolanic reactions, another part remains mobile and available and over time the residual $Ca(OH)_2$ penetrates the carbonated pumice and microcrystals of secondary calcite form inside the pores (Collepardi, 1990). Crystal fragments of alkali feldspar, clinopyroxene and mica are also present.

TA4

Sample TA4 is characterised by cryptocrystalline matrix (Fig. 4e-f). Aggregates make up approximately 30% of the mortar and are of volcanic origin, composed by pumice fragments, mostly

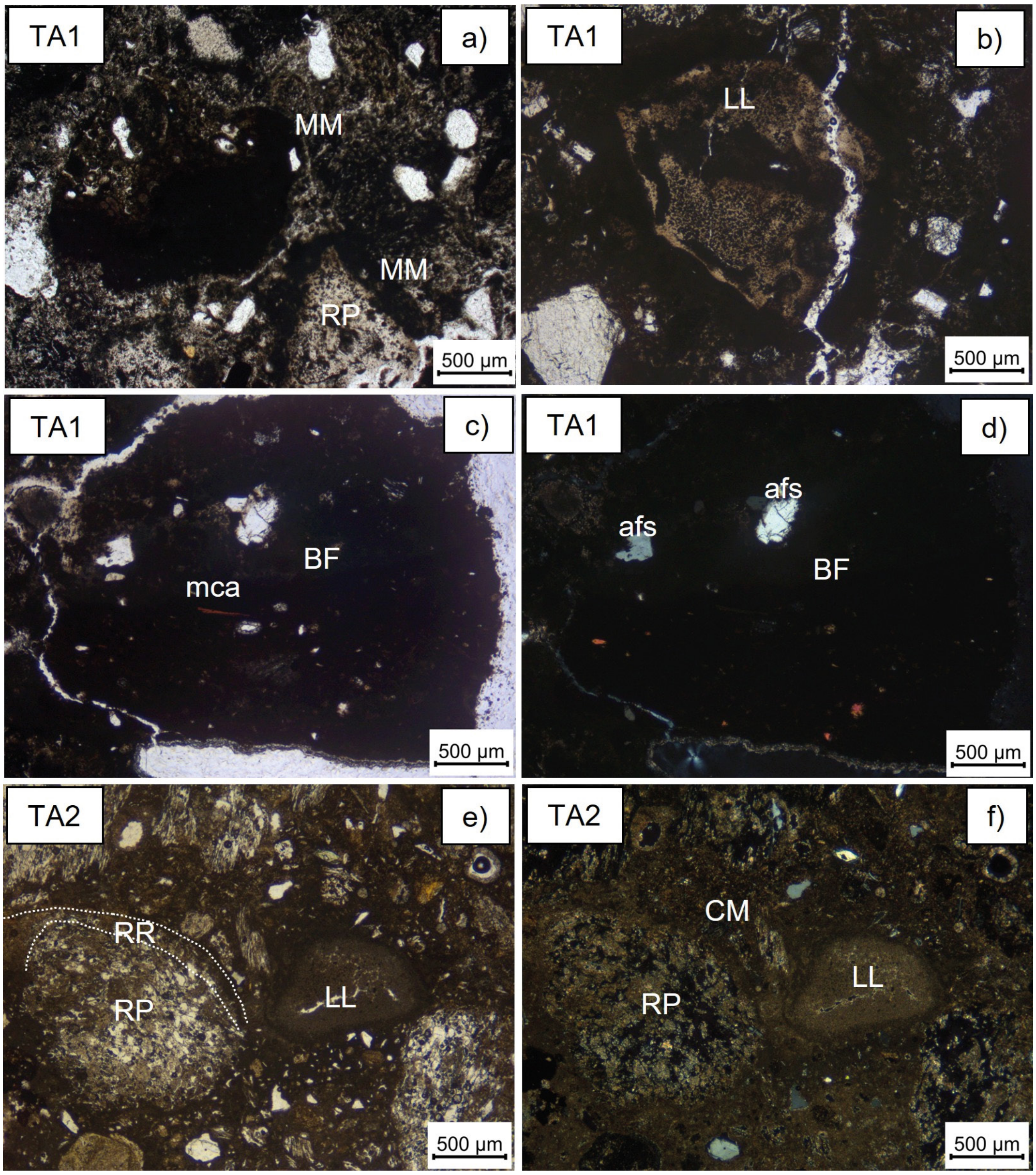

Fig. 3 - Microphotographs of mortar components (PPL: plane polarised light, a-c,e; CPL: crossed polarised light, d,f) of samples TA1 (a-d) and TA2 (e-f). (a) micritic matrix (MM) and recarbonated pumice (RP); (b) lime lump (LL); (c-d) brick fragment (BF), mica (mca) and alkali feldspar fragments (afs); (e-f) recarbonated pumice (RC) with reaction rim (RR, dashed white line) and lime lump (LL). Abbreviations, where possible, from Warr (2021).

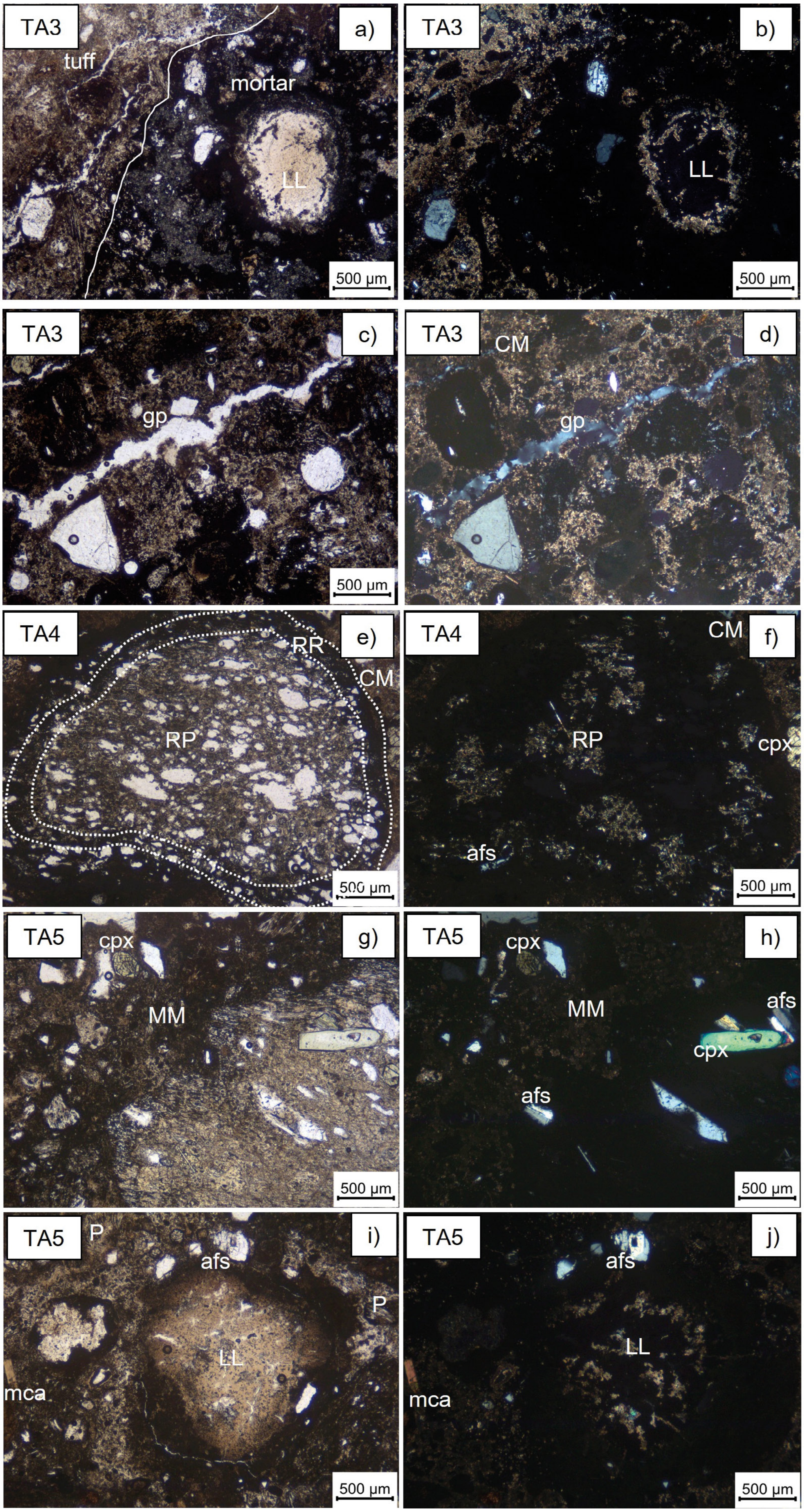

Fig. 4 - Microphotographs of mortar components (PPL: plane polarised light, left; CPL: crossed polarised light, right) of samples TA3 (a-d), TA4 (e-f) and TA5 (g-j). (a-b) contact between tuff and mortar (solid white line) and lime lumps (LL) in the mortar portion of the sample; (c-d) cryptocrystalline matrix (CM), and gypsum (gp); (e-f) cryptocrystalline matrix (CM) and recarbonated pumice (RP) with reaction rim (RR, dashed white line); (g-h) micritic matrix (MM) and fragments of clinopyroxene (cpx), alkali feldspar (afs); (i-j) lime lump (LL), pumice (P) and fragments of alkali feldspar (afs) and mica (mca). Abbreviations, where possible, from Warr (2021).

altered for recarbonation processes and displaying well-defined reaction rims (Fig. 4e-f), along with crystal fragments of alkali feldspar and clinopyroxene (Fig. 4e-f).

TA5

Sample TA5 (Fig. 4g-j) displays micritic matrix (Fig. 4g-h) containing rounded lime lumps (Fig. 4i-j). Aggregates make up about 40% of the mortar and are of volcanic origin, represented by pumice fragments (Fig. 4i-j), alkali feldspar, clinopyroxene and mica (Fig. 4g-j).

TA6 and TA-6_BR

The interface between the mortar (TA6) and the brick (TA6_BR) is clearly visible in the sample TA6 (Fig. 5a-b). The binder fraction of TA6 sample is primarily composed by cryptocrystalline and subordinately micritic matrix (Fig. 5c-d). As in previous samples, rounded lime lumps are also present (Fig. 5c-d). Aggregate fractions constitute approximately 40% of the mixture and are mainly composed of pumice fragments exhibiting distinct reaction rims and signs of recarbonation (Fig. 5e-h). Crystal fragments of alkali feldspar and mica (Fig.5c-h) are also present, along with calcite crystals (Fig. 6g-h).

The brick sample TA6_BR show a bimodal distribution of grains (50 to 200 μm) containing about the 30% of inclusions. The ceramic body exhibits no optical activity. The main inclusions are represented by quartz, mica, alkali feldspar, clinopyroxene and mica (Fig. 5a-b).

Mineralogical analysis

XRPD results confirmed the occurrence of lime-based mortar with volcanic aggregate, as shown by analyses reported in Tab. 2 and Fig. 6. Since no fragments of carbonate rocks were found within the mortars, it is possible to state that all the calcite present in the samples belongs to the binder fraction of which it is the most abundant phase, along with subordinate gypsum. Moreover, all

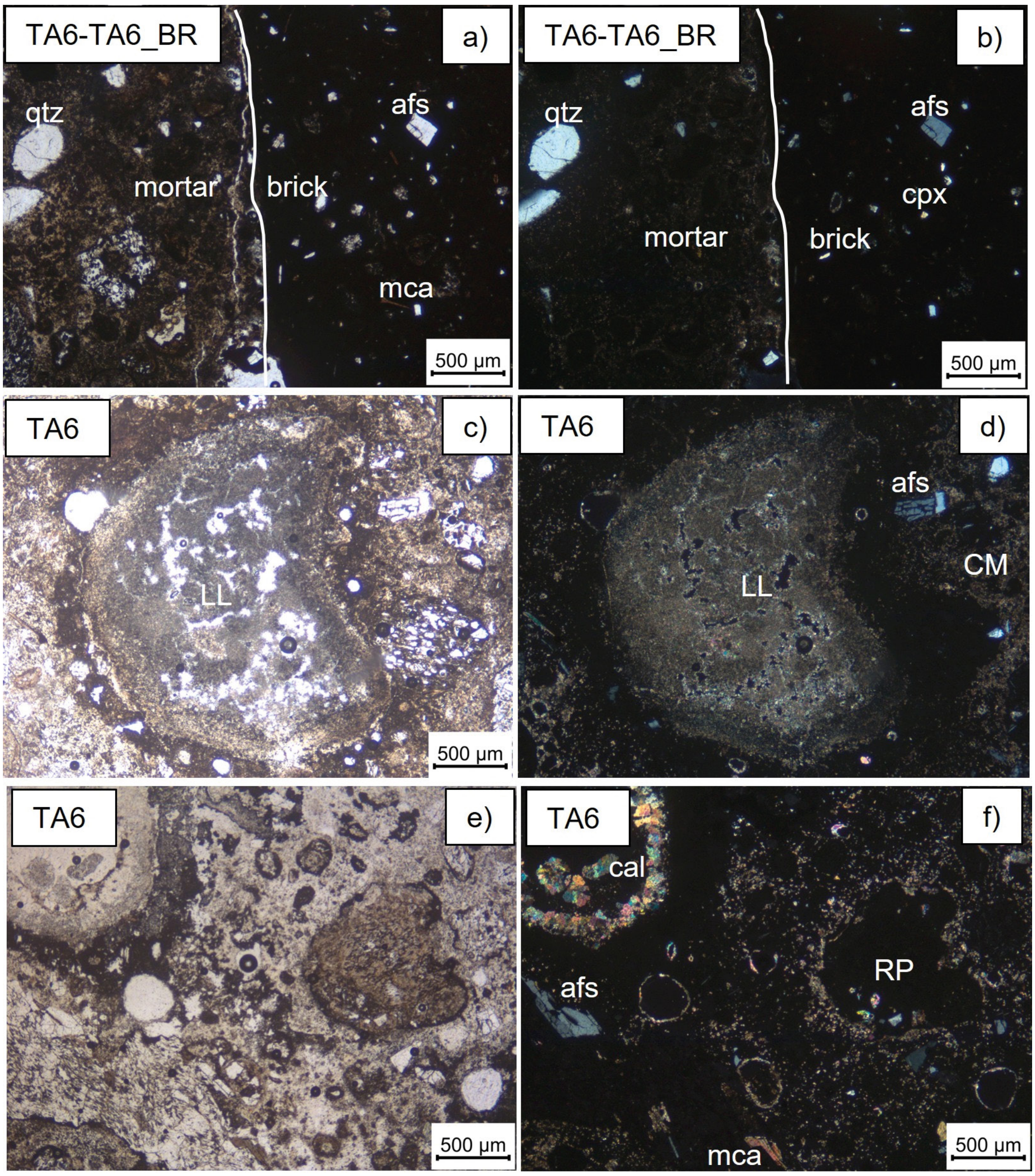

Fig. 5 - Microphotographs of mortar components (PPL: plane polarised light, a, c, e; CPL: crossed polarised light, b, d, f) of samples TA6 (a-f) and TA6_BR (a-b). (a-b) contact between mortar (TA6) and brick (TA6_BR) as shown also in Fig. 2, along with alkali feldspar (afs) and mica (mca) fragments; (c-d) lime lump (LL); (e-f) recarbonated pumice (RP), calcite (cal) and mica (mca) fragment. Abbreviations, where possible, from Warr (2021).

the XRPD analyses of the analysed samples are characterised by the presence of halite. XRPD analyses also showed the presence of phillipsite, chabazite and analcime (zeolites), along with alkali feldspar, pyroxene and mica. Brick sample TA6_BR is characterised by quartz, calcite, alkali feldspar, clinopyroxene, mica and hematite (Fig. 6, Tab. 2).

DISCUSSION AND CONCLUSIONS

The present minero-petrographic study conducted on samples from the Tempio di Apollo aimed at obtaining information about the preparation techniques and the provenance of the used raw materials. The results provided insights into both 1) main characteristics of the various components and 2) methods for mortar production.

The study revealed mortars mix design characterised by the use of lime as binder, which is relatively compact and exhibits a micritic and cryptocrystalline texture, with predominant volcanic aggregates, along with the sporadic presence of ceramic fragments.

The calcareous raw materials and alteration phases provided valuable insights into both the provenance and production technology. Regarding the source location, of both the lime used for the mortar preparation and volcanic aggregates is of local origin. The lime is likely to have its origin from the carbonate reliefs bordering the Campanian Plain (Morra et al., 2010).

As regards volcanic aggregates, minero-petrographic characterisation suggests that they are trachytes, constituted by cineritic matrix, fragments of pumice, and by the zeolites phillipsite, chabazite and analcime, along with alkali feldspar, clinopyroxene and mica (Fig. 6, Tab.2). Based on the regional geological context, the volcanic aggregates analyzed are of local origin. The presence

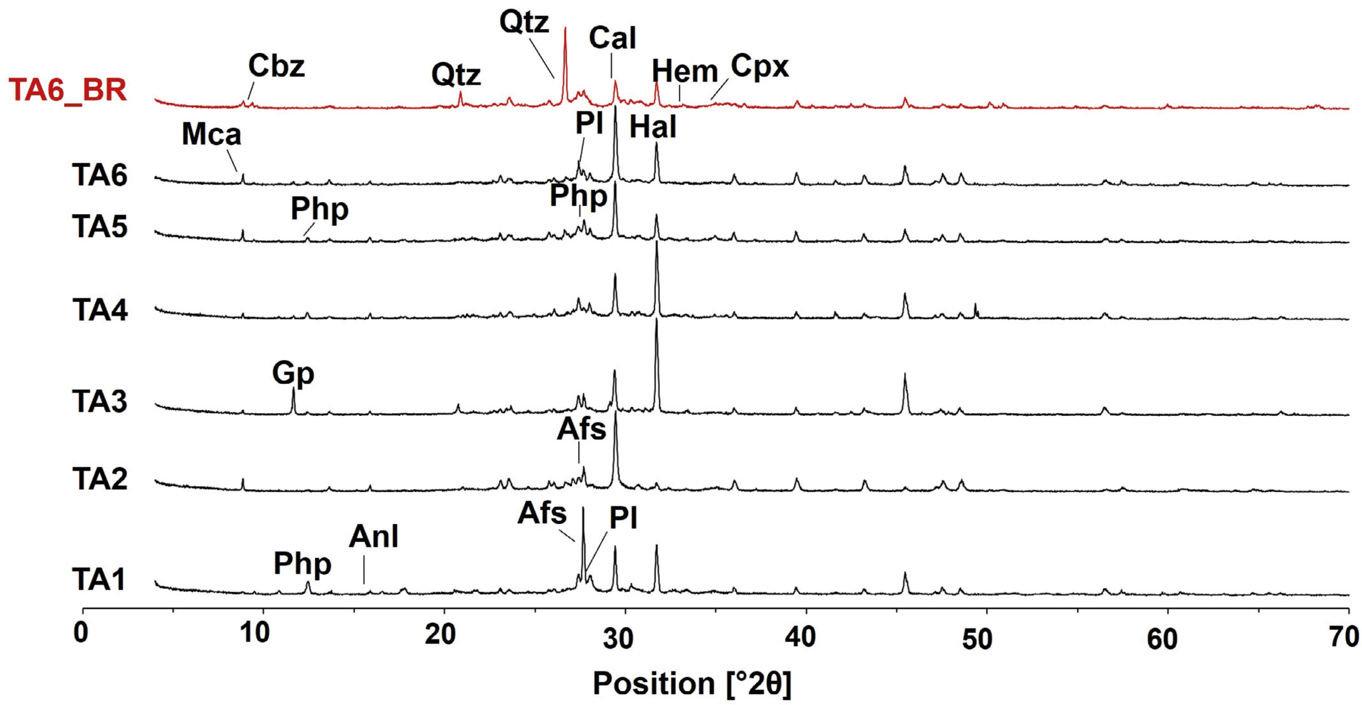

Fig. 6 - XRPD patterns of the investigated samples. Abbreviations from Warr (2021): Cal= calcite; Hal= halite; Qtz= quartz; Php= phillipsite; Cbz= chabazite; Anl= analcime; Mca= mica; Afs= alkali feldspar; Pl= plagioclase; Hem= hematite; Gp= gypsum.

Table 2 - X-Ray Powder Diffraction (XRPD) analysis of the investigated samples.

Sample	Type	Location	Cal	Hal	Qtz	Php	Cbz	Anl	Mca	Afs	Pl	Hem	Cpx	Gp
TA1	bedding mortar +tuff	ground	X	X		X	X	X	X	X	X			
TA2	bedding mortar	ground	X	X		X		X	X	X	X			
TA3	bedding mortar+tuff	wall	X	X		X		X	X	X				X
TA4	bedding mortar	wall	X	X		X		X	X	X				X
TA5	bedding mortar	ground	X	X		X	X	X	X	X	X			
TA6	bedding mortar+brick	ground	X	X		X	X	X	X	X	X			X
TA6_BR	brick	ground	X	X	X		X		X	X		X	X	

Abbreviations from Warr (2021): Cal= calcite; Hal= halite; Qtz= quartz; Php= phillipsite; Cbz= chabazite; Anl= analcime; Mca= mica; Afs= alkali feldspar; Pl= plagioclase; Cpx= clinopyroxene; Hem= hematite; Cpx= clinopyroxene; Gp= gypsum.

of phillipsite, analcime, and chabazite constitutes a characteristic zeolitic assemblage commonly associated with volcanic deposits from the Phlegraean Fields. This mineralogical signature is particularly indicative of the Neapolitan Yellow Tuff (NYT), one of the most important and extensively distributed eruptive products resulting from volcanic activity of the area, dating approximately 15,000 years BP (de Gennaro, 1999, International Crystal). Moreover, given the proximity of the Tempio di Apollo archaeological site to Miseno, it is reasonable to assume that the tuff derives from the most recent eruptions of the Phlegraean Fields (e.g., Monte Nuovo; Piochi et al., 2005; D'Oriano et al., 2005).

The provenance of ceramic fragments could not be determined with certainty, but it suggests the possible reuse of diverse fictile materials. The use of raw materials used to produce ceramic fragments of artificial materials (e.g., bricks), should have had the role in protecting from moisture in water-bearing structures such as baths and aqueducts (Eramo et al., 2008; Lezzerini et al., 2014, 2019; Miriello et al., 2018; Sitzia et al., 2020; Wei et al., 2020; Rispoli et al., 2024). Quartz detected in the TA6 mortar is, in fact, related to inclusions in ceramic fragments (Fig. 6, Tab.2). Given the small number of cocciopesto fragments found within the samples analysed in this study, it is possible to hypothesize that ceramic fragments derive from recycled material from different ceramic productions and can be considered an early example of reuse and recycling practices. The presence of neo formed phases gypsum and halite is indicative of distinct formation processes: i) gypsum is a common weathering product derived by the calcite sulphation, a process driven by pH reduction due to the dissolution of atmospheric SO_2 (Ricca et al., 2023), while ii) the presence of halite is likely attributable to ancient interactions the marine aerosol deposition (Rispoli et al., 2015).

This study also shed a light on the preparation techniques. As described by Vitruvius in De Architectura, Romans knew how to produce a suitable mortar mix, including a uniform calcination

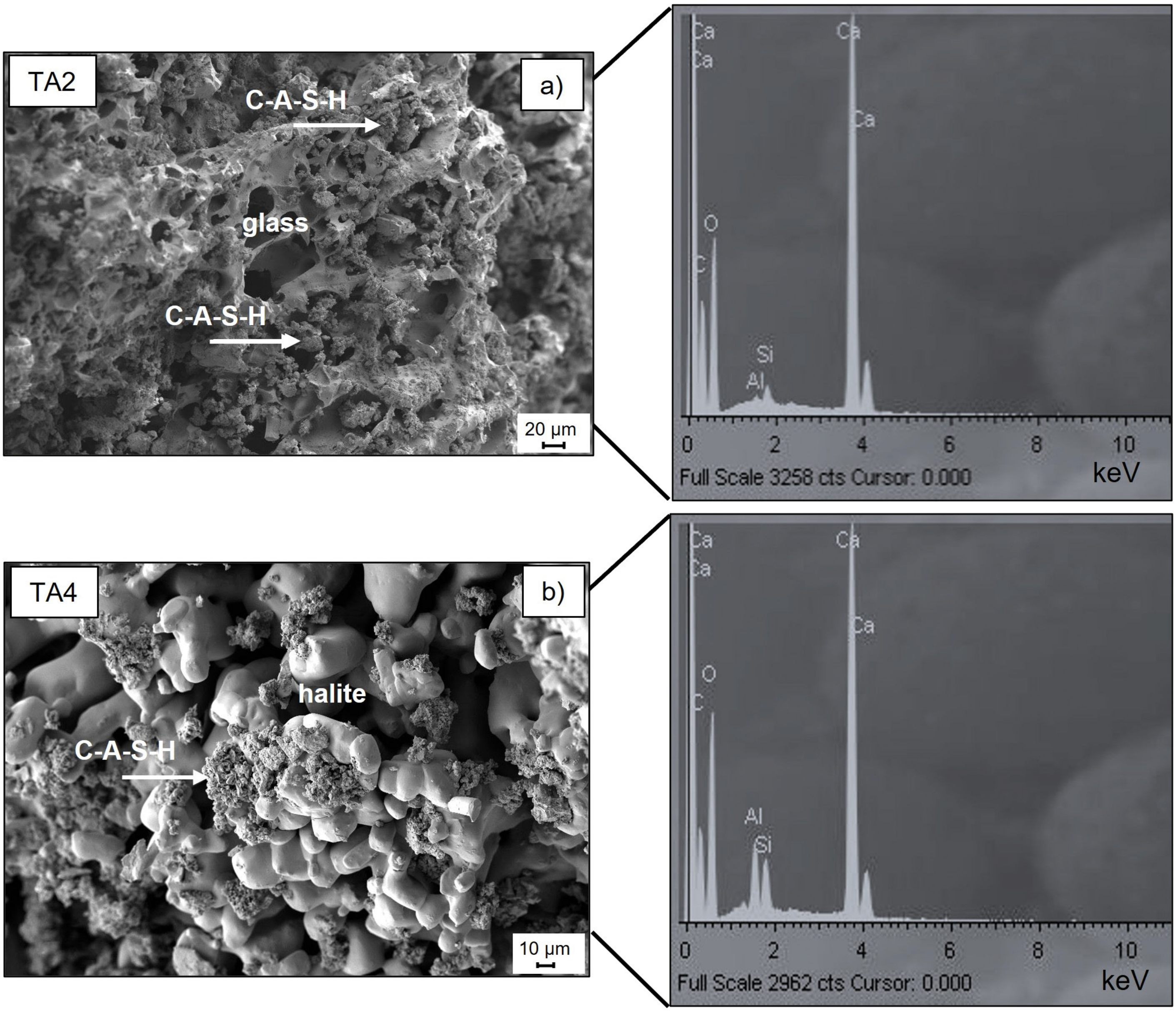

Fig. 7. SEM-SE images showing C-A-S-H gel formation in samples TA2 and TA4 and relative EDS spectra on the right. Halite crystals are also visible.

of the limestone and a careful determination of the correct proportions of lime, aggregate and water. Lime slaking was carried out in special tanks, then the lime was transferred into large "liming pits". Subsequently, using a hoe with a very long handle, the mixture was rubbed to eliminate lumps from the mixture and to make the sand penetrate the lime, until the mixture appeared perfectly homogeneous (Adam, 1994). The analyses conducted in this study indicate that this preparation technique was not fully observed, as the presence of numerous rounded lime lumps (Figs. 3, 4 and 5), which representing lime poorly slaked during the preparation of the mortar and partially recarbonated, suggests errors during the calcination process. According to Moropoulou et al. (2005) and Barba et al. (2009), lime lumps represent non-reacted lime due to a bad slaking process caused by a low water/lime ratio.

Moreover, the presence of calcite (Fig. 5g-h) is probably due to the presence of lime that has not reacted with water and may be related to a calcareous residue that has not been completely calcined (Adam, 1994; Cairoli 2018). It is also possible to hypothesize that the analyzed mortars are hydraulic, since pumice show reaction rims at the interface between the aggregate and the binder (Fig. 3 and 4). Their presence testifies the so-called pozzolanic reaction between the lime and the silica and alumina of the volcanic materials, leading to the formation of hydrated calcium silicates (C-S-H) and hydrated calcium aluminates (C-A-H; Rispoli et al., 2020; Montesano et al., 2022). The occurrence of C-A-S-H gel has been confirmed through SEM analysis (Fig. 7) as a coating network enveloping the pumice glass and filling the voids and interstitial spaces between the pumiceous aggregates. Its presence is indicative of the hydraulic character of the mortar (Middendorf & Knöfel, 1998; Rispoli et al., 2016). Halite crystals, exhibiting the typical well-defined cubic shape, smooth surfaces ad a glass-like luster (Buck et al., 2011), are also visible in Fig. 7, as already detected by XRPD analyses (Fig. 6, Tab. 2). The presence of halite crystals alongside C-A-S-H phases likely results from localised microenvironments created by salt crystallisation in the mortar's pore network.

The study of Roman mortars - such as those from the Tempio di Apollo - highlights the pivotal role of a blend combining locally sourced lime, volcanic materials, and recycled ceramics to produce durable, hydraulic mortars, fundamental to Roman engineering success. These materials and techniques, often tailored to local resources, resulted in mortars with remarkable longevity and resilience. This can be attributed to the chemical and mineralogical complexity of the mortars, which includes self-healing properties linked to lime clasts and pozzolanic reactions. The adaptability and empirical knowledge embedded in Roman mortar production not only shaped ancient architecture but continue to inspire modern material science and conservation practices.

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