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The art of building in the Roman period (89 B.C. – 79 A.D.): Mortars, plasters and mosaic floors from ancient *Stabiae* (Naples, Italy)

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HIGHLIGHTS

- Villa San Marco is one of the best-preserved *otium villae* of the Bay of Naples.
- A multilayer technology was adopted for mortar-based materials.
- Lime binder and calcite/silicates/pozzolan aggregate were mixed following a precise recipe for each layer.
- Volcanic and sedimentary raw materials from surroundings were exploited.

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ABSTRACT

This current research is focused on the mineralogical and petrographic characterisation of mortar-based materials from Villa San Marco in the ancient *Stabiae* (modern Castellammare di Stabia, Napoli), an outstanding example of Roman *otium villae*, and aims at recognising the technology used by the ancient skilled workers.

Several analytical techniques were used such as digital videomicroscopy, optical microscopy, digital image analysis, scanning electron microscopy coupled with EDS analysis and Quantitative Powder X-ray Diffraction.

A multi-layer technology characterised the plasters; the scratch coat was made with lime mortars mixed with a pozzolanic lightweight aggregate and *cocciopesto*, required ingredients providing a quick-setting and a better adhesion with the support. As far as the *arriccio* layer is concerned, the mix-design is a lime mortar with volcanic sand as the aggregate and a minor content of pozzolan and/or *cocciopesto* to enhance the workability of the mortar in order to correct any error due to the roughness of the scratch coat. The plaster *s.s.* was the removable support in case of mistakes, and gave a lighter colour to the preparation layer of the frescoes. The last thin layer, prepared with lime mortars and a carbonate aggregate, is characterised by low porosity in order to avoid pigment adsorption. The painting technique was a fresco with *encaustication*.

In contrast, the mortars of the building structures were made with lime added to a pozzolanic aggregate (volcanics and *cocciopesto*), giving a quick setting during the implementation of the yellow tuff *opus reticulatum*.

The *rudera* and *nuclei* of the mosaics were built with abundant volcanic sand and *cocciopesto* mixed with the lime, producing a more resistant surface, and finally the *tesserae* were fixed exclusively with lime. The white and black colours of the mosaics were produced by local limestone and tephritic lava.

The results permitted an evaluation of the high level of specialization of both the workers and the artists that built and decorated these maritime villas. Moreover, the collected data highlighted the wide potentiality of the materials cropping out in the environs of the Somma-Vesuvius volcanic complex. This research aims at furnishing a useful reference for future restoration action in Villa San Marco and the other Roman villas in this area.

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1. Introduction

Archaeological mortar-based materials are the products of the complex technological knowledge and ability of ancient skilled workers. An approach to the characterisation of these construction materials permits recovering some fundamental information regarding the material culture of these ancient craftsmen. In the past years, numerous research studies have been devoted to the study of such building materials, focusing on: an accurate identification and classification of mortar-based materials [1–5]; the composition and provenance of the raw materials [6–11]; the use of mortar-based materials for the identification of construction phases of a building in different epochs [12,13], also using ^{14}C dating [14], and knowledge building techniques [15–20].

The above-mentioned knowledge represents a fundamental premise for suitably and accurately planning the conservation of Cultural Heritage [21–26]. To this end, the present research aims at characterising the mortar-based materials (mortars, plasters and mosaic floors) from Villa San Marco, one of the *otium villae* of ancient *Stabiae*.

The archaeological site of *Stabiae* represents one of the most important concentrations of seaside Roman villas of the Mediterranean area. The site was the subject of a large restoration and conservation program involving local stakeholders such as the "Soprintendenza Archeologica di Pompei" (the Superintendence of Archaeology of Pompeii, the Restoring Ancient *Stabiae* (RAS) Foundation and other research institutions. Despite the archaeological relevance of this site, no literature data concerning the material characterisation (such as mortars, building stones and ceramics) is available. In contrast, a plethora of studies has focused on archaeological findings and their raw materials and technology from the neighbouring and world famous settlement of *Pompeii* and, more generally, from the Campania region [7,8,13,27–41].

This current study is a first attempt to fill this gap by means of a detailed mineralogical and petrological investigation on a set of mortar-based materials collected from Villa San Marco, probably the most important among the so-called *otium villae* of ancient *Stabiae*. This investigation aims at providing new data on the composition and provenance of raw materials used in the Vesuvius-environs during the Roman period, as well as an evaluation of the implementation construction techniques linked to the ability of the skilled workers, before the Vesuvius eruption of 79 A.D. Furthermore, this research can represent a valuable tool for the preservation and restoration of the Villa San Marco frescoed masonries that, despite a good state of conservation, are subject to some weathering such as efflorescence, discoloration and convex deformation.

2. Brief archaeological outlines

The Vesuvius-environs land has always attracted people since the Early Bronze Age thanks to the large availability of natural resources and soil fertility [33,42–48]. In contrast, several natural episodes, such as the Campanian Ignimbrite eruption (39 ka) [49–53], that of *Pompeii* in 79 A.D. and the eruption in 472 A.D. [54,55], deeply modified the landscape from a geological and geomorphological point of view with a consequential impact on human activities [45].

Ancient *Stabiae* is located on the Pianoro di Varano, a plateau in the junction between the Lattari Mountains carbonate ridge and the Sarno River flood plain (Fig. 1).

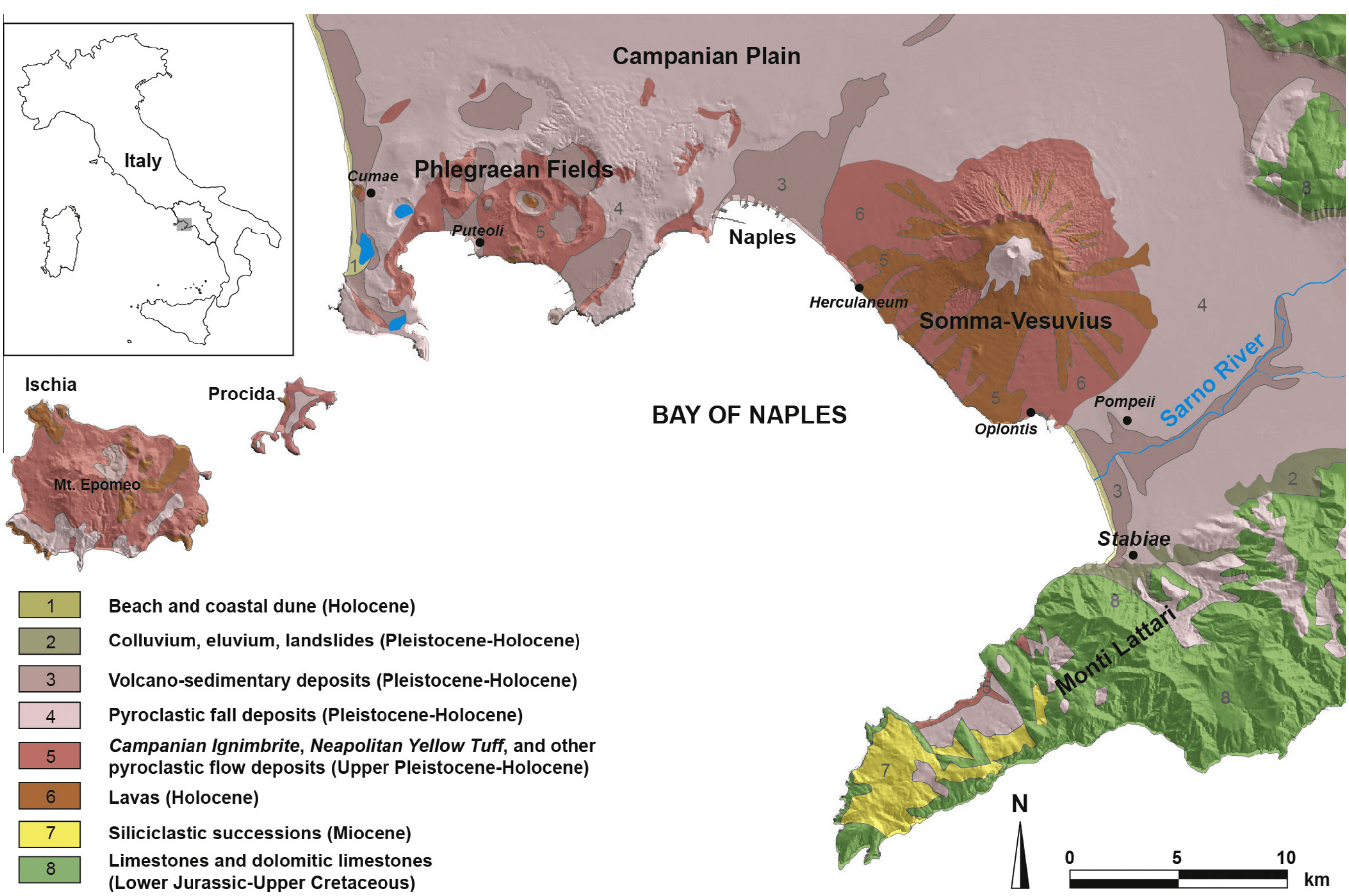

Fig. 1. A geological sketch of the Bay of Naples area and the location of the archaeological site of ancient *Stabiae* (modified after Bonardi et al. [56]).

This settlement nowadays consists of several *otium villae* and rustic villas dated between 89 B.C. and 79 A.D., discovered by King Charles IV of Naples in 1749.

During its life span, this *otium villae* complex was subjected to several geological risks related to the seismic and volcanic activity of this area, such as the earthquake in 62 A.D. Subsequently, it was completely buried by pyroclastics (several metres thick) from the 79 A.D. eruption, and subsequent slope instabilities, which in turn altered the ancient coastline [57].

Villa San Marco is a huge building of approximately 11,000 m^2, of which only a part has been excavated (Fig. 2). The walls are made of tuff in *opus reticulatum* (Fig. 3a), often covered with frescoed plasters. The decorative motifs are predominantly realised by imitation polychrome orthostates (Fig. 3b) and the columns are made by *opus latericium* covered by mortars simulating monolithic columns. The floors are decorated with mosaics constituted by white and black *tesserae*, often representing geometrical shapes (Fig. 3c, d and e).

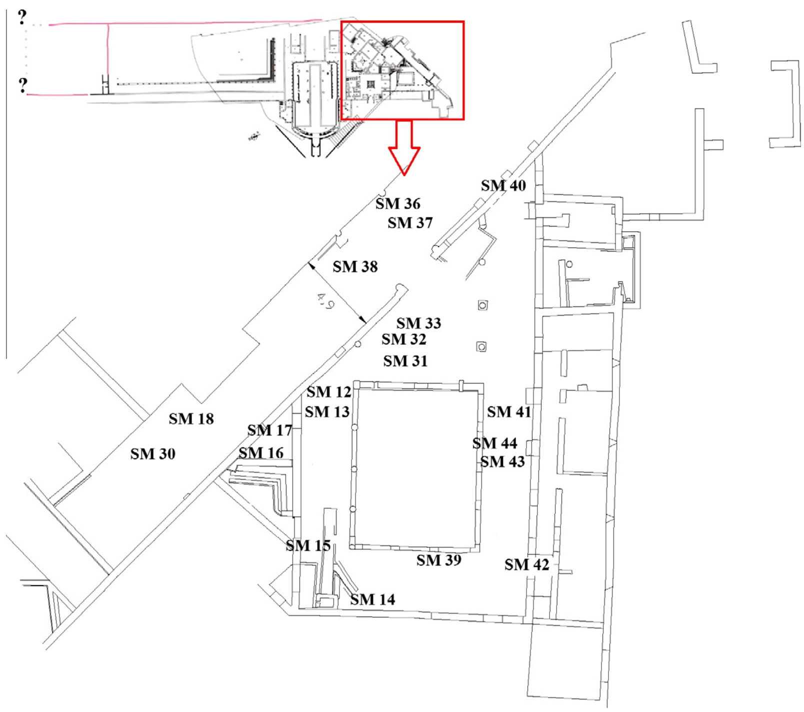

Fig. 2. The excavation plan of Villa San Marco with the twenty samples collected in a sector of the villa.

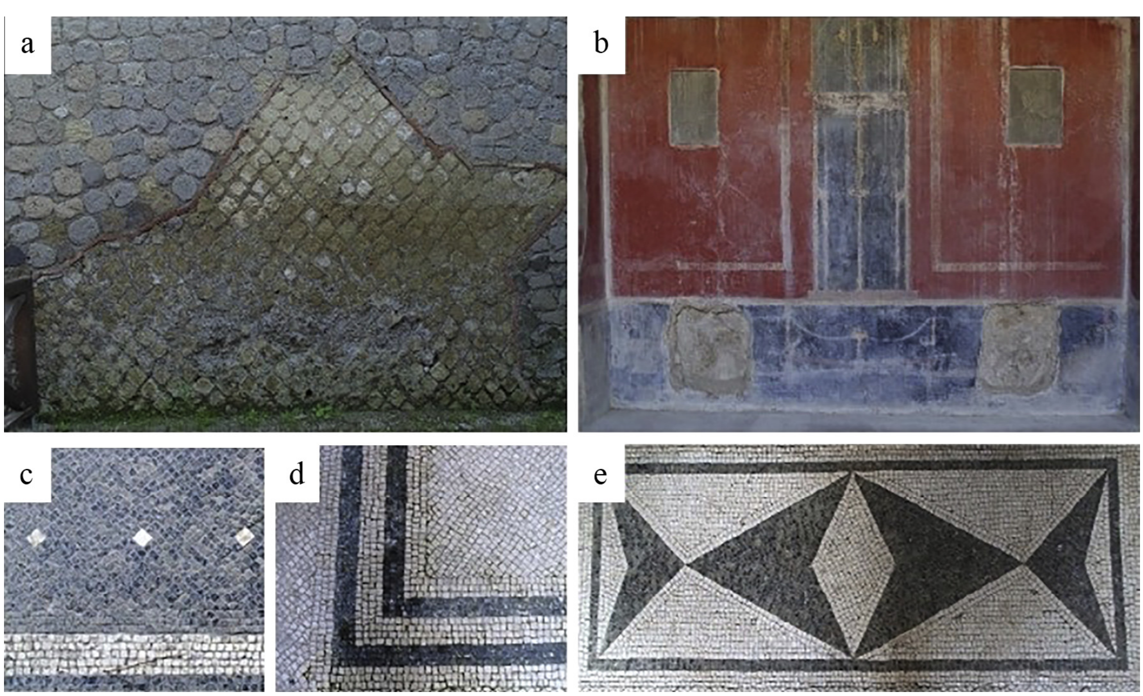

Fig. 3. Some architectural features of Villa San Marco: a) the original masonry in *opus reticulatum* separated by modern restoration; b) fresco mural painting realised in imitation polychrome orthostates; c), d) and e), geometrical shapes in mosaic floors.

The whole building and decorative techniques permit attributing Villa San Marco to patrician families or influent politicians from Rome, although the real owner is still unknown.

3. Materials and methods

Twenty samples of mortar-based materials from Villa San Marco were collected (10 plasters, 8 mortars and 2 mosaic floors, Table 1). A sketch section of a typical stratigraphic sequence in a Roman plaster [17,58] is reported in Fig. 4. On these bases, the multi-layer samples (plasters and mosaics) were progressively labelled from the innermost layer (0 layer) to the outer layers (up to 3), excluding the mural painting. As far as the floors with mosaics are concerned, another typical stratigraphic sequence was adopted (starting from the lowermost to the uppermost layer): *rudus* (layer 0), *nucleus* (layer 1), *supranucleus* (layer 2) and mosaic *tesserae* [18].

The samples were characterised from a mineralogical and petrographic point of view according to the UNI-EN 11305:2009 and UNI-EN 11176:2006 [59,60].

Thick sections were also observed via Digital Video Microscope (DVM, Leica DVM 2000) for the description of the layered structure of the samples and to determine the textural features of the aggregate. Mineralogical features, as well as the binder-to-aggregate ratio (B/A, including the pores in the binder), were investigated by Optical Microscopy observations (OM; Olympus BX-60 equipped with a digital camera Olympus DP10). Digital Image Analyses (DIA) using software ImageJ (see [28,29] and references therein) permitted the quantitative determination of textural parameters.

The Grain Size Distribution (GSD) using minimum Feret values (mF), which permitted the calculation of the Krumbein φ (where $\varphi = -\log$ (mF)) [29,61,62] was obtained by density histogram (R version 3.0.2) [63]. The morphological characteristics of the grains were described in terms of circularity ($C = 4\pi(A/p^2)$, where A = area, p = perimeter) and roundness ($R = 4(A/\pi(M)^2$, where M = major axis), according to UNI 11176-2006 recommendations.

The mineralogical composition was determined by Quantitative Powder X-ray Diffraction (QPXRD) using a Panalytical X'Pert Pro diffractometer (CuKα radiation, 40 kV, 40 mA, 3–80° 2θ scanning interval, RTMS detector, 0.017° equivalent step size, 60 s per step equivalent counting time). Quantitative mineralogical analyses were performed using combined Rietveld [64] and reference intensity ratio meth-

Table 1
Textural features of plasters, bedding mortars and mosaic floors, determined by DIA on DVM images.

ID_sample	ID_layer	Function	Textural features of aggregate						Thickness (mm)	
			Circularity	Roundness	ϕ_{min}	ϕ_{max}	ϕ_{medium}	S(ϕ)	min.	max.
Plasters										
SM 12	SM 12-0	Scratch coat	0.34	0.31	0.13	7.44	4.89	1.28	–	⩾18
	SM 12-1	*Arriccio*	0.79	0.63	0.67	4.95	2.48	0.97	2.0	6.0
	SM 12-2	Plaster s.s.	0.75	0.61	−0.83	4.87	3.25	1.24	7.0	9.0
	SM 12-3	Preparation	0.74	0.59	−0.17	6.21	3.87	1.12	3.0	3.0
SM 13	SM 13-1	*Arriccio*	0.78	0.63	0.26	4.46	2.39	1.07	2.5	3.0
	SM 13-2	Plaster s.s.	0.72	0.58	−0.39	5.09	2.86	1.20	4.5	5.5
	SM 13-3	Preparation	0.72	0.58	0.85	4.53	2.84	0.98	2.2	2.5
SM 14	SM 14-1	*Arriccio*	0.78	0.63	−0.15	4.49	1.79	0.97	–	⩾12
	SM 14-2	Pla./Prep.	0.68	0.55	−0.53	4.21	2.53	1.12	7.0	7.5
SM15	SM 15-1a	Arriccio	0.73	0.61	−0.31	3.90	2.54	0.93	–	⩾5
	SM 15-1b	*Arriccio*	0.75	0.61	−0.23	4.63	2.69	0.99	13.0	14.0
	SM 15-2	Pla./Prep.	0.62	0.49	0.50	4.96	3.16	1.22	2.0	2.6
SM 16	SM 16-2	Plaster s.s.	0.73	0.58	−0.70	5.11	2.92	1.46	–	⩾8
	SM 16-3	Preparation	0.68	0.56	0.03	4.82	3.21	1.25	0.4	0.5
SM 17	SM 17-0	Scratch coat	0.30	0.14	−1.51	5.79	3.72	0.99	–	⩾5
	SM 17-1	*Arriccio*	0.76	0.62	1.32	4.95	2.62	0.79	8.0	9.0
	SM 17-2	Plaster s.s.	0.67	0.56	−0.15	5.87	3.55	1.29	3.5	4.0
	SM 17-3	Preparation	0.66	0.54	0.73	5.38	3.47	1.05	4.0	4.5
SM 31	SM 31-1	*Arriccio*	0.73	0.57	−0.09	1.29	0.77	0.25	–	⩾5
	SM 31-2	Plaster s.s.	0.68	0.57	−0.67	5.22	2.60	1.53	4.5	5.0
	SM 31-3	Preparation	0.70	0.56	0.20	4.80	3.09	0.94	2.5	3.0
SM32	SM 32-1	Arriccio	0.70	0.55	−1.46	4.42	2.43	1.09	–	⩾4.5
	SM 32-2	Plaster s.s.	0.70	0.58	−1.46	4.10	1.90	1.36	9.5	10.0
	SM 32-3	Preparation	0.67	0.55	0.39	5.49	3.23	0.99	2.5	3.0
SM 33	SM 33-1	*Arriccio*	0.76	0.62	−0.10	4.80	2.64	1.05	–	⩾7
	SM 33-2	Plaster s.s.	0.66	0.51	−0.77	4.47	2.30	1.46	5.5	6.0
	SM 33-3	Preparation	0.67	0.52	0.52	5.04	3.28	1.14	4.3	5.0
SM 37	SM 37-0	Scratch coat	0.47	0.43	−0.02	5.44	3.49	1.03	–	⩾11
	SM 37-2	Pla./Prep.	0.66	0.52	0.54	5.42	3.56	1.16	3.8	4.5
Bedding mortars										
SM 36	–	Bedding	0.54	0.43	−0.09	5.73	3.76	1.00	–	–
SM 38	–	Bedding	0.59	0.51	−3.03	6.68	3.77	1.12	–	–
SM 39	–	Bedding	–	–	–	–	–	–	–	–
SM 40	–	Bedding	–	–	–	–	–	–	–	–
SM 41	–	Bedding	–	–	–	–	–	–	–	–
SM 42	–	Bedding	0.35	0.32	2.00	6.75	4.66	1.22	–	–
SM 43	–	Bedding	–	–	–	–	–	–	–	–
SM 44	–	Bedding	–	–	–	–	–	–	–	–
Mosaic floors										
SM 18	SM 18-0	*Rudus*	0.73	0.60	−0.82	5.38	3.04	1.09	–	⩾7
	SM 18-1	*Nucleus*	0.77	0.62	−0.29	3.79	2.15	0.93	1.0	2.0
	SM 18-2	*Supranucleus*	–	–	–	–	–	–	1.0	2.0
SM 30	SM 30-0	*Rudus*	0.78	0.63	−0.60	4.46	2.51	0.91	–	⩾15
	SM 30-2	*Supranucleus*	–	–	–	–	–	–	1.0	2.0

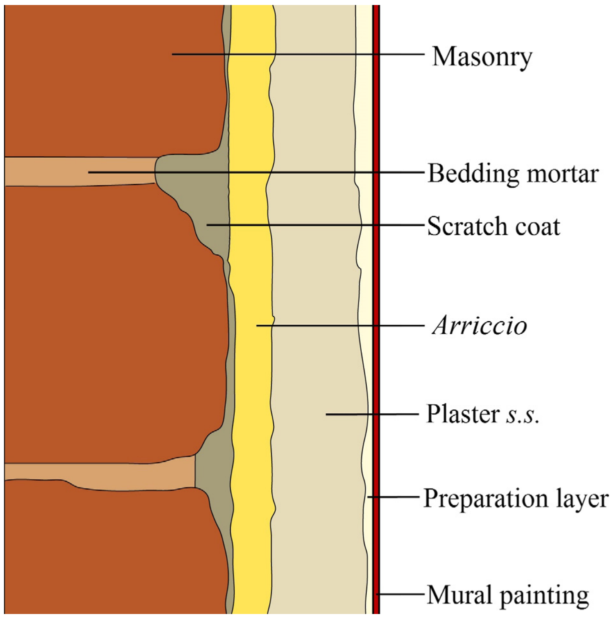

Fig. 4. Sketch section of a typical Roman plaster (inferred from the treatise of Vitruvius [58]).

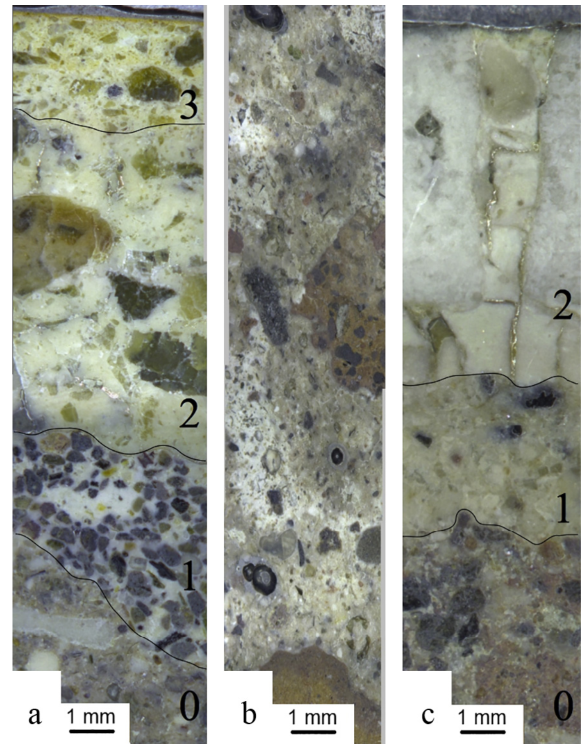

Fig. 5. DVM images of plaster SM 12 (a), bedding mortar SM 38 (b) and mosaic floor SM 30 (c) in which different layers (labelled 0, 1, 2 and 3) can be distinguished.

ods (RIR [65]), by means of TOPAS 4.2 software (BRUKER AXS Company). In this way, the estimation of both crystalline and amorphous (disordered) phases was obtained [66]. Atomic starting coordinates for identifying crystalline phases were taken from literature [67]. Phases with a partial or unknown crystal structure (low ordered or amorphous phases) were quantified by adding a "peaks phase" with the TOPAS software.

Micro-textural observations and micro-chemical analyses were carried out by Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (SEM/EDS; Zeiss EVO HD 15 coupled with Oxford Xmax-80 microanalysis, and Zeiss AURIGA FESEM coupled with Oxford INCA-200 microanalysis) on representative samples. Two plasters (SM 12 and 17) and three bedding mortars (SM 36, 40 and 42) were chosen for SEM/EDS analyses due to the fact that they showed clear pozzolanic reaction rims around the volcanics and/or ceramic fragments; moreover, the plasters were selected among those that showed a complete layering from the *arriccio* to the preparation layer.

4. Results

4.1. Texture of the mortar-based materials

4.1.1. Plasters

The plasters of Villa San Marco showed a multilayer technology (Fig 5a; Table 1). Among the examined samples, only two of them (SM 12 and SM 17) presented a complete stratigraphic sequence (Fig. 5a) that was composed of, from the innermost to the outermost layer, a scratch coat (layer 0), *arriccio* (layer 1), plaster *s.s.* (layer 2) and a thin preparation layer for the mural painting (layer 3). The other samples showed a partial stratigraphy: samples SM 13, SM 15 (in which the *arriccio* layer appears doubled), SM 31, SM 32 and SM 33 (three layers), samples SM 14, SM 16 and SM 37 (only two layers). The thickness of each single layer ranged from a few millimetres up to 18 mm or over. The innermost layer always represents the thickest layer.

The scratch coat layer constitutes the anchorage element to the masonry and it is found in samples SM 12, SM 17 and SM 37; GSD widely ranges from very fine silt to a very fine pebble with the highest density in the range of the coarse silt. Grains showed low circularity and roundness, and were poorly sorted (Table 1).

The *Arriccio* layer aimed at regularizing the flatness and vertical mistakes due to the scratch coat surface. These layers showed a GSD with the highest density in the range of fine sand. The aggregate was mostly moderately sorted, excluding sample SM 31-1, that was very well sorted (S(φ) = 0.25). Circularity and roundness were medium-high (Table 1).

The outermost layers represent the support for the mural painting and are usually represented by a plaster *s.s.* layer along with a thin preparation layer. Nevertheless, in samples SM 14, SM 15 and SM 37, it was not possible to distinguish these two layers: the only layer observed most probably contemporarily performed the function of the plaster *s.s.* and the preparation layer (Table 1). Furthermore, layer SM 37-2 was directly joined to layer SM 37-0 (scratch coat).

The GSD shows the highest density in the range of the medium and coarse sand. The aggregate was poorly sorted whereas the circularity and roundness of grains were slightly lower than those observed in the *arriccio* (Table 1). The boundary between the plaster and the preparation layer was often hard to define, being textural changes, specifically a slightly finer GSD and a more sorted aggregate plaster *s.s.*, the only evidence.

Fig. 6 shows density histogram distribution of textural features (circularity, roundness and φ) for sample SM 12, as a representative of all the investigated plasters.

4.1.2. Bedding mortars

The bedding mortars showed a GSD between medium-fine silt and medium-coarse sand with the highest density in the range of fine silt. Grains were poorly sorted, with a medium-low value of circularity and roundness (Table 1). Sample SM 38 (Fig. 5b) showed an aggregate characterised by a bimodal distribution with a fine fraction (silty-arenaceous) and a coarser fraction (conglomeratic), made up of dark red grains.

4.1.3. Mosaic floors

The stratigraphic sequence was complete in SM 18 (Fig. 5c), whereas in SM 30 it showed a single preparatory mortar-based layer, most probably a *rudus* layer.

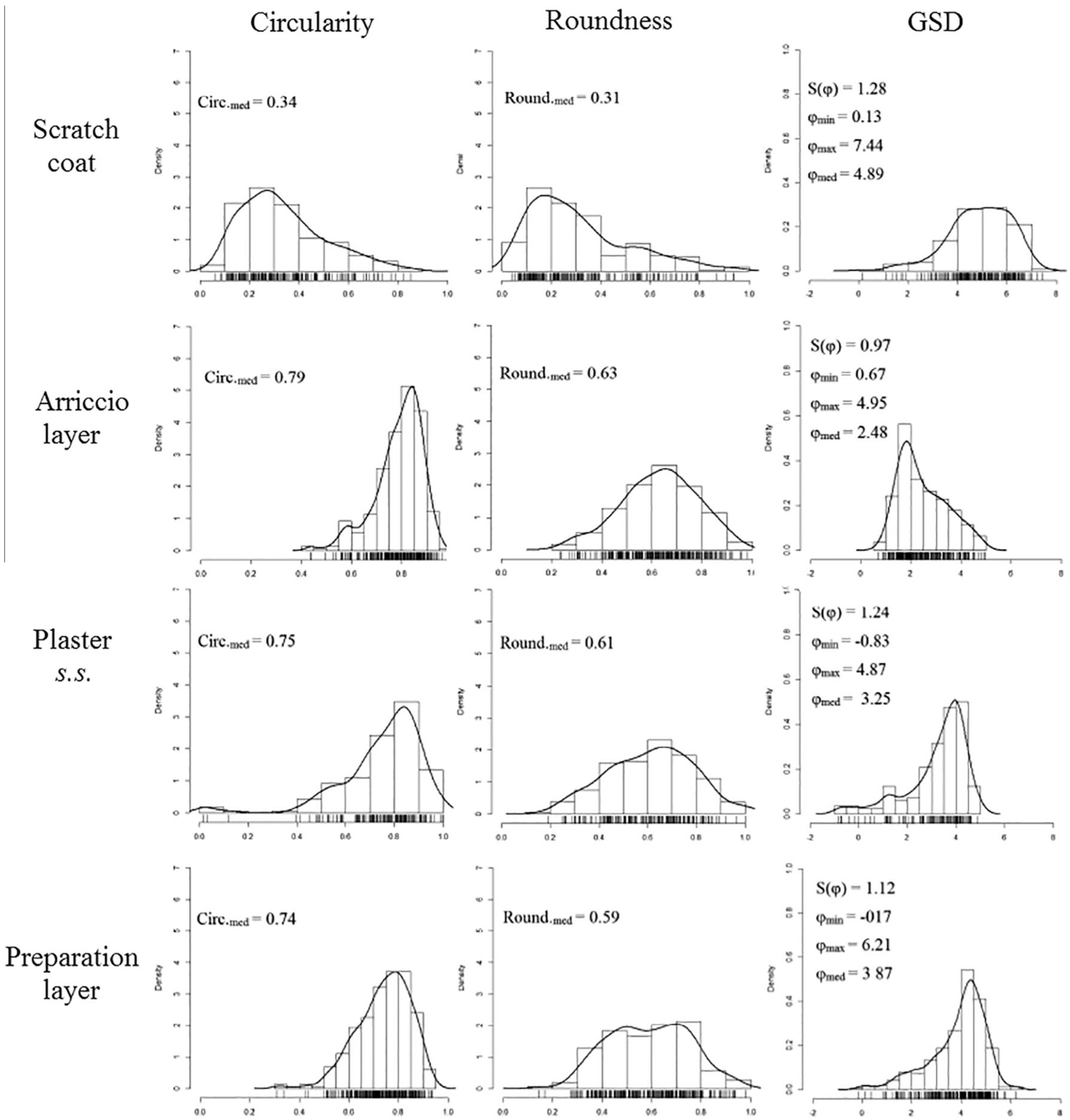

Fig. 6. Density histograms of textural features of the aggregate in sample SM 12: average values of circularity (Circ.) and roundness (Round.), along with statistical descriptors of GSD (φ) are reported (S(φ) = standard deviation of φ values).

The aggregate used for the preparatory mortar-based layers (*rudus* and *nucleus*) was a fine sand. Sorting ranged from 0.91 to 1.09 and grains showed a medium-high value of circularity and roundness (Table 1). In sample SM 18, the boundaries between the *rudus*, *nucleus* and *supranucleus* were continuous and sharp. The aggregate in the *supranucleus* layers was absent (SM 18) or located among the *tesserae* (SM 30).

4.2. Optical microscopy

4.2.1. Plasters

Scratch coat layers were formed by a lime binder (Fig. 7a) with an aggregate content ranging from 44% (SM 17) to 52% (SM 12) and composed of pyroclastic fragments (pumice and glass shards), sanidine, ceramic fragments (commonly *cocciopesto*) showing frequent reaction rims (Fig. 7b) and minor scoriae, Ca-rich pyroxene, calcite, leucite-bearing tephritic lava fragments, plagioclase, mica, and rare olivine and oxides. Leucite crystals in the lava fragments often turned into analcime. The B/A ratio ranges between 0.92 and 1.27 (Table 2).

The *arriccio* layers (Fig. 7 c, d, e and f) were formed by a lime binder mixed to volcanic aggregate and minor *cocciopesto*. The aggregate in the *arriccio* layers is composed of tephritic lava fragments (Fig. 7c), volcanic scoriae, Ca-rich pyroxene, sanidine (Fig. 7d), plagioclase, pumice and *cocciopesto*. Limestone fragments, olivine, quartz and oxides also occur. The aggregate in sample SM 17-1 showed a higher content in Ca-rich pyroxene in relation to the other *arriccio* layers. Shards of bivalve shells also occur (Fig. 7e). In samples SM 13-1, SM 14-1, SM 15-1a, SM 15-1b and SM 32-1, the aggregate was characterised by abundant limestone fragments (Fig. 7f, Table 3). The aggregate generally ranges from 37% (SM 32 and SM 33) to 44% (SM 12 and SM 13) and the B/A ratio is between 1.27 and 1.70; a higher aggregate content (almost 60%) and a B/A ratio of 0.66 was only evidenced in sample SM 14-1 (Table 2).

Both the *arriccio* and scratch coat layers showed frequent unmixed lumps of a binder (Fig. 7g), most probably due to an incomplete mixing of the mortar components [15].

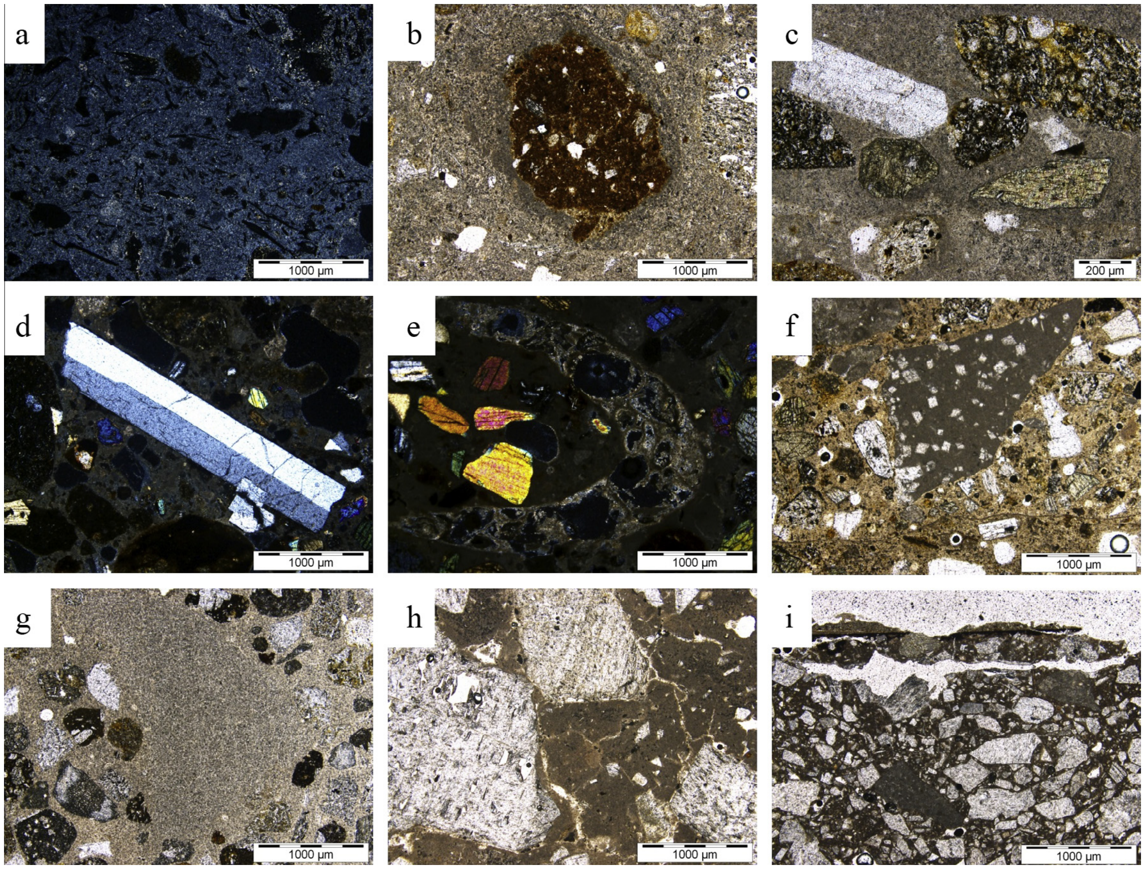

Fig. 7. Micrographs of plasters: a) lime matrix in the scratch coat, SM 12, crossed polarised light; b) rim reaction around a ceramic fragment in the scratch coat, SM 12, plane polarised light; c) tephritic lava fragments, clinopyroxenes and plagioclase in the *arriccio*, SM 12, plane polarised light; d) sanidine in the *arriccio*, SM 15, crossed polarised light; e) clinopyroxenes and shell shard of bivalve organism in the *arriccio*, SM 17, crossed polarised light; f) carbonate fragment in the *arriccio*, SM 15, plane polarised light; g) unmixed lump in the *arriccio*, SM 31, plane polarised light; h) limestone fragments aggregate in the plaster s.s., SM 16, plane polarised light; i) carbonate aggregate, wall painting covered by a thin coat of vanish and faint detachment in the preparation layer, SM 13, plane polarised light.

Plasters *s.s.* were lime mortars with a limestone aggregate (Fig. 7h) and subordinately mica and oxides. The aggregate generally ranged from 19% (SM 15) to 42% (SM 14) and the B/A ratio was very high (up to 4.26) (Table 2). Only sample SM 13-2 presented a low amount of a volcanic aggregate.

Finally, the preparation layers were composed of a lime mortar with limestone fragments (Fig. 7i) and traces of oxides. The aggregate ranged from 37% (SM 13) to 46% (SM 32) and the B/A ratio was between 1.17 and 1.63. The wall paintings were generally covered by a thin coat of varnish (Fig. 7i), absent only in SM 15 and in SM 37. In some preparation layers, some faint detachments were also observed (Fig. 7i) [69].

4.2.2. Bedding mortars

The bedding mortars were formed by a lime binder and an aggregate content ranging from 40% (SM 36) to 53% (SM 38) and constituted by pyroclastic fragments (pumice and volcanic glass shards, Fig 8a), and a low amount of *cocciopesto* (<2%, Table 2). The B/A ratio ranges between 0.89 and 1.50.

Sample SM 38 presented the highest content of ceramic fragments (Fig. 8b). The matrix is microcrystalline and shows subrounded pores and shrinkage fissures. The rims of the ceramic fragments showed frequent reaction rims. Vegetal frustules (organic admixtures) were observed in sample SM 40 (Fig. 8c).

4.2.3. Mosaic floors

The preparatory layers of the mosaic floors (*rudera* and *nuclei*) were all constituted by a lime mortar with a volcanic crystalline aggregate and low amounts of carbonate, *cocciopesto* and rare pumice (Table 2). The microcrystalline matrix showed some lumps, often affected by shrinkage fissuring (Fig. 9a). DIA results showed that an aggregate was among 46–48% for the *rudera* layers and 29% for the *nucleus* in SM 18-1. The aggregate was formed by *cocciopesto* (Fig. 9b), Ca-rich pyroxene, scoriae, lava and limestone fragments, plagioclase, sanidine and a lower amount of pumice, olivine, quartz, mica and oxides. The B/A ratio was between 1.08 and 1.17 for the *rudera* layers and 2.45 for the *nucleus*.

The white *tesserae* were a limestone, namely a biomicrite. Erosion (Fig. 9c) and crusts (Fig. 9d) on the surface of *tessera* were noticed. On the other hand, the black *tesserae* were effusive igneous rocks with a fine-textured porphyritic structure and a tephritic composition. Leucite (Fig. 9e and f), plagioclase, Ca-rich pyroxene and rare amphibole were identified.

Supranucleus (the bedding lime for the *tesserae*) was a cryptocrystalline calcite in both mosaic floors; here the lack of aggregate defined a network of cracks between the grain and *tesserae* compromising their adhesion (Fig. 9c and e).

4.3. QPXRD

The quantitative PXRD results (Table 3) highlighted that calcite is the principal mineral occurring in the mortar-based materials along with plagioclase, alkali feldspar and clinopyroxene as the mineral phases of the aggregate; minor quartz, leucite and/or analcime also occur. Some samples also show traces of mica and hematite in the aggregate fraction.

Table 2
Mineralogical analysis by DIA on OM micrographs. Abbreviations from [68]: Cal, calcite; P.R., pozzolanic reaction; Pum, pumice; Sc, scoria; Coc, cocciopesto; Afs, alkali feldspar; Cpx, clinopyroxene; Mic, mica; Hem, hematite; Carb, carbonate fragment; Pl, plagioclase; Ol, olivine; Qz, quartz; Op.s., opaque substances; A, aggregate; B/A, binder-to-aggregate ratio. Legend: xxx, abundant; xx, frequent; x, scarce; tr, traces).

ID_sample	ID_layer	Binder	P.R.	Pum	Sc	Coc	Afs	Cpx	Mic	Hem	Lava	Carb	Pl	Ol	Qz	Op.s.	A (%)	B/A
Plasters																		
SM 12	SM 12-0	Cal	Yes	36	1	6	8	tr	tr	1	tr	tr	tr	–	–	1	**52**	0.92
	SM 12-1	Cal	No	2	8	2	5	8	–	1	11	tr	7	tr	1	1	**44**	1.28
	SM 12-2	Cal	No	–	–	–	–	–	2	–	–	25	–	–	–	tr	**27**	2.70
	SM 12-3	Cal	No	–	–	–	–	–	–	–	–	44	–	–	–	tr	**44**	1.27
SM 13	SM 13-1	Cal	No	x	x	tr	x	x	–	tr	x	xx	tr	–	–	tr	**44**	1.27
	SM 13-2	Cal	No	–	x	–	tr	x	–	–	tr	xx	–	–	–	tr	**26**	2.85
	SM 13-3	Cal	No	–	–	–	–	–	–	–	–	xxx	–	–	–	tr	**37**	1.70
SM 14	SM 14-1	Cal	Yes	x	x	tr	x	x	–	tr	x	xx	tr	–	–	tr	**60**	0.67
	SM 14-2	Cal	No	–	–	–	–	–	–	–	–	54	–	–	–	2	**42**	1.38
SM 15	SM 15-1a	Cal	No	x	x	x	x	x	–	tr	x	xx	tr	–	–	tr	**42**	1.38
	SM 15-1b	Cal	No	x	x	x	x	x	–	tr	x	xx	tr	–	–	tr	**43**	1.33
	SM 15-2	Cal	No	–	–	–	–	–	–	–	–	xx	–	–	–	tr	**19**	4.26
SM 16	SM 16-2	Cal	No	–	–	–	–	–	–	–	–	xx	–	–	–	tr	**28**	2.57
	SM 16-3	Cal	No	–	–	–	–	–	–	–	–	xxx	–	–	–	tr	**41**	1.44
SM 17	SM 17-0	Cal	Yes	xxx	x	x	x	x	–	tr	x	–	tr	–	–	tr	**44**	1.27
	SM 17-1	Cal	No	tr	7	1	4	24	tr	tr	3	tr	1	1	tr	tr	**41**	1.44
	SM 17-2	Cal	No	–	–	–	–	–	–	–	–	xxx	–	–	–	tr	**24**	3.17
	SM 17-3	Cal	No	–	–	–	–	–	–	–	–	xx	–	–	–	tr	**40**	1.50
SM 31	SM 31-1	Cal	No	x	x	–	x	x	–	tr	x	xx	tr	–	–	tr	**39**	1.56
	SM 31-2	Cal	No	–	–	–	–	–	–	–	–	xx	–	–	–	tr	**27**	2.70
	SM 31-3	Cal	No	–	–	–	–	–	–	–	–	xxx	–	–	–	tr	**44**	1.27
SM 32	SM 32-1	Cal	No	x	x	tr	x	x	–	tr	x	xx	tr	–	–	tr	**37**	1.70
	SM 32-2	Cal	No	–	–	–	–	–	–	–	–	xx	–	–	–	tr	**40**	1.50
	SM 32-3	Cal	No	–	–	–	–	–	–	–	–	xxx	–	–	–	tr	**46**	1.17
SM 33	SM 33-1	Cal	No	x	x	tr	x	x	–	tr	x	–	tr	–	–	tr	**37**	1.70
	SM 33-2	Cal	No	–	–	–	–	–	–	–	–	xx	–	–	–	tr	**23**	3.35
	SM 33-3	Cal	No	–	–	–	–	–	–	–	–	xxx	–	–	–	tr	**38**	1.63
SM 37	SM 37-0	Cal	Yes	xxx	x	x	x	x	–	tr	x	–	tr	–	–	tr	**48**	1.08
	SM 37-2	Cal	No	–	–	–	–	–	–	–	–	xx	–	–	–	tr	**29**	2.45
Bedding mortars																		
SM 36	–	Cal	Yes	xxx	tr	x	xx	x	–	tr	x	–	tr	–	–	x	**40**	1.50
SM 38	–	Cal	Yes	xxx	x	xx	x	x	–	tr	x	–	tr	–	–	x	**53**	0.89
SM 39	–	Cal	Yes	xxx	x	x	xx	x	–	tr	x	–	tr	–	–	x	–	–
SM 40	–	Cal	Yes	xxx	x	x	xx	x	–	tr	x	–	tr	–	–	x	–	–
SM 41	–	Cal	Yes	xxx	x	x	xx	x	–	tr	x	–	tr	–	–	x	–	–
SM 42	–	Cal	Yes	29	tr	2	10	1	–	1	tr	tr	tr	–	–	2	**45**	1.24
SM 43	–	Cal	Yes	xxx	x	x	xx	x	–	tr	x	–	tr	–	–	x	–	–
SM 44	–	Cal	Yes	xxx	x	x	xx	x	–	tr	x	–	tr	–	–	x	–	–
Mosaic floors																		
SM 18	SM 18-0	Cal	No	1	5	19	1	8	tr	tr	5	4	2	1	tr	1	**48**	1.10
	SM 18-1	Cal	No	x	x	xx	x	x	tr	tr	tr	x	x	tr	tr	tr	**29**	2.45
	SM 18-2	Cal	No	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
SM 30	SM 30-0	Cal	Yes	x	x	xx	x	x	tr	tr	tr	x	x	tr	tr	tr	**46**	1.17
	SM 30-2	Cal	No	–	tr	–	–	tr	–	–	–	–	–	–	–	–	–	–

Quantitative Rietveld analyses also permitted highlighting the presence of a Low Ordered or Amorphous Phase (LO-AP), most probably ascribable to the volcanic glassy phase (pumice and scoriae) and the C-S-H and C-A-H phases; the latter formed after pozzolanic reactions between the lime and volcanic glasses or *cocciopesto* grains [13], as observed in thin section and SEM observation (see hereafter).

X-ray patterns also permitted the identification of the different layers of plasters and mortars from the Villa San Marco masonry, as a function of calcite – silicates – LO-AP content (Table 3; Fig. 10).

The highest calcite content (>90%) was measured in plaster *s.s.* and SM 32-1. This is due to the fact that calcite was the main component of both the aggregate and the binder. Consequently, plaster *s.s.* and SM 32-1 also accounted for the lowest LO-AP content. Silicates are generally absent in these layers, except for samples SM 13-2 and SM 17-2 (Table 3).

In contrast, the highest LO-AP content occurs in the scratch coat and bedding mortars samples. The diagram in Fig. 10 also highlights the low content of the crystalline phases (silicates) in the aggregate of the scratch coat and bedding mortars samples, mainly diffused in the *arriccio* layers.

According to their mineralogical composition (Table 3) and texture by OM, the white *tesserae* are composed of limestone, while the black *tesserae* are fragments of tephrite.

4.4. SEM/EDS

The description of the morphological features of the mortar-based materials must take into account, above all, the typology of the predominant pores that can occur in different forms, such as intra-particle pores and inter-particle pores. They are represented by rounded pores (RP), typical of the water evaporation

Table 3
Quantitative Powder X-ray Diffraction analysis (main abbreviations from [68]: Cal, calcite; Qz, quartz; Pl, plagioclase; Afs, alkali feldspar; Cpx, clinopyroxene; Lct, leucite; Anl, analcime; Mic, mica; Hem, hematite; Am, amorphous; tr, traces).

ID_sample	ID_layer	Cal	Qz	Pl	Afs	Cpx	Lct	Anl	Mic	Hem	Am
Plasters											
SM 12	SM 12-0	40	–	6	10	tr	–	–	–	–	43
	SM 12-1	27	–	14	13	18	1	1	–	1	24
	SM 12-2	91	–	–	–	–	–	–	tr	–	8
SM 13	SM 13-1	73	–	8	4	7	tr	–	–	–	7
	SM 13-2	91	–	4	tr	1	tr	–	–	–	3
SM 14	SM 14-1	17	–	18	38	18	–	1	tr	tr	7
	SM 14-2	92	–	–	–	–	–	–	–	–	8
SM 15	SM 15-1a	32	–	14	28	16	tr	1	tr	tr	8
	SM 15-1b	30	–	14	30	19	tr	1	tr	tr	5
	SM 15-2	93	–	–	–	–	–	–	–	–	7
SM 16	SM 16-2	93	–	–	–	–	–	–	–	–	7
SM 17	SM 17-0	50	2	7	9	5	–	–	tr	–	27
	SM 17-1	27	–	6	8	45	tr	1	1	–	12
	SM 17-2	89	1	4	–	–	–	–	tr	–	6
SM 31	SM 31-1	45	–	14	20	18	–	–	–	–	2
	SM 31-2	95	–	–	–	–	–	–	–	–	5
SM 32	SM 32-1	89	tr	–	–	–	–	–	–	–	12
	SM 32-2	99	–	–	–	–	–	–	–	–	1
SM 33	SM 33-1	72	–	7	7	4	–	1	tr	–	9
	SM 33-2	99	–	–	–	–	–	–	–	–	1
SM 37	SM 37-0	62	–	10	15	3	–	1	tr	–	9
Bedding mortars											
SM 36	SM 36	29	–	11	8	1	5	–	–	–	45
SM 38	SM 38	40	–	9	8	1	–	–	1	–	40
SM 39	SM 39	13	–	15	24	–	–	2	3	tr	43
SM 40	SM 40	4	–	6	7	4	–	–	1	–	79
SM 41	SM 41	16	–	13	11	–	–	–	4	1	55
SM 42	SM 42	20	–	10	12	–	–	–	5	tr	52
SM 43	SM 43	28	–	14	13	–	–	–	5	1	39
SM 44	SM 44	36	–	13	11	–	–	–	5	1	34
Mosaic floors											
SM 18	SM 18-*tessera*	3	–	34	–	25	22	3	3	–	10
SM 30	SM 30-2	81	–	–	4	–	–	–	tr	–	15

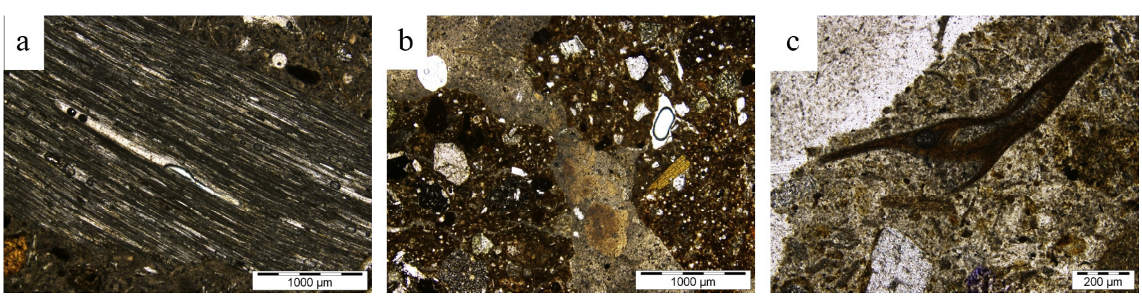

Fig. 8. Micrographs of bedding mortars: a) pumice, SM 36, plane polarised light; b) ceramic fragments, SM 38, plane polarised light; c) frustule, SM 40, plane polarised light.

process, and shrinkage fissures (SF), related to the volumetric changes of the mortar during the drying and the carbonation process [23].

In the scratch coat layers, a predominance of intra-particle pores in relation to inter-particle pores (RP and SF) was observed, mostly due to the presence of pumices (Fig. 11a).

EDS analyses provided interesting results in terms of chemical variations along the boundaries between the ceramic fragments (*cocciopesto*) and the surrounding binder (SM 12-0 sample, Fig. 12). A migration of Si, Al and Fe from the *cocciopesto* to the binder was observed, triggering the consequent formation of the C-S-H and C-A-H phases (see also [12,13]). The formation of these phases, attesting a pozzolanic activity, and the almost total absence of SF, improved the cohesion between the grain and the binder.

In the *arriccio* layers, intra-particle pores sensibly decrease and RP prevail (Fig. 11b).

The low content of an aggregate in plasters *s.s.* defined the prevalence of SF in relation to intra-particle and RP. According to Arizzi et al. [23], such SF, often extended up to the grain/matrix boundary (Fig. 11c), and most probably compromised the mechanical performances of the mortar.

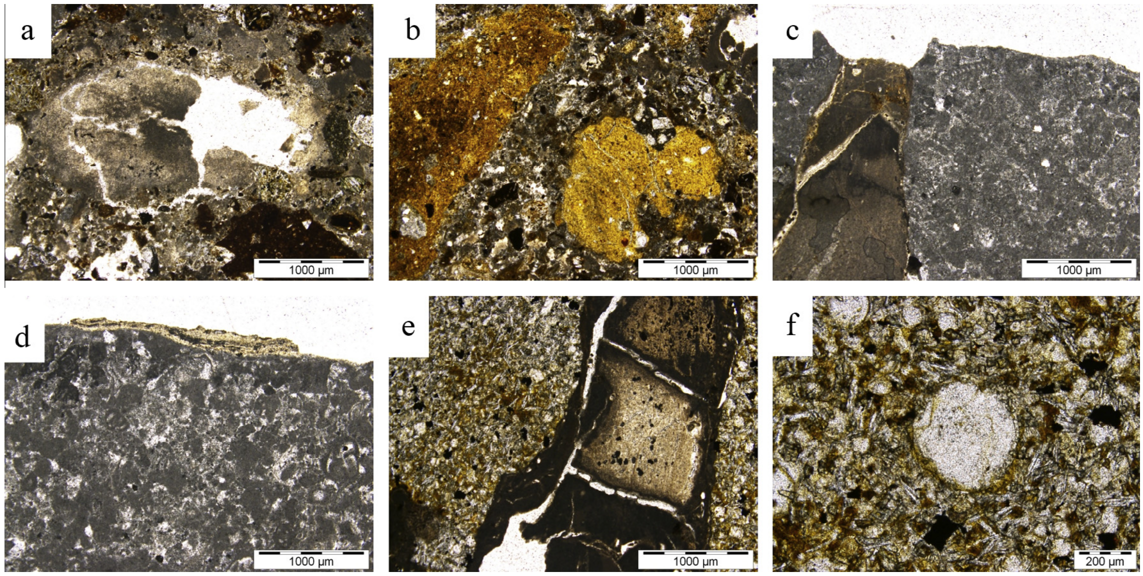

Fig. 9. Micrographs mosaics floors: a) unmixed lump with shrinkage fissures in *nucleus*, SM 18, plane polarised light; b) *cocciopesto* in *rudus*, SM 30, plane polarised light; c) *Supranucleus* and limestone white *tesserae*, SM 18, plane polarised light; d) Crust on white *tesserae*, SM 18, plane polarised light; e) *Supranucleus*, SM 30, plane polarised light; f) Leucite-bearing tephritic lava black *tesserae*, SM 30, plane polarised light.

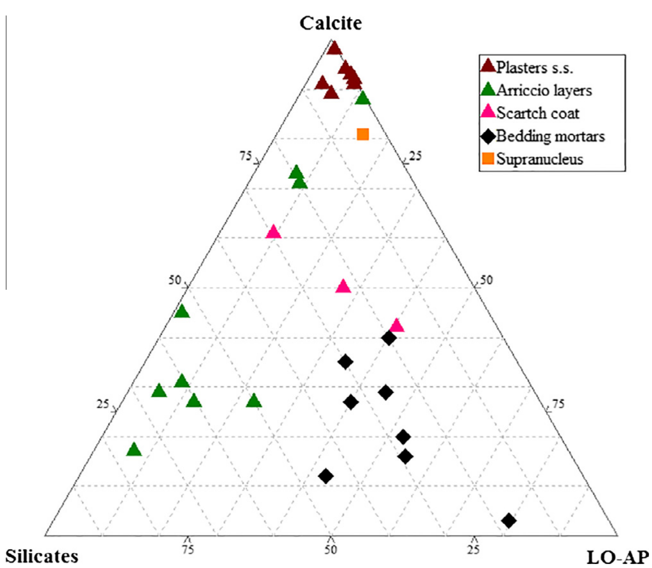

Fig. 10. Ternary diagram calcite – silicates – LO-AP (QPXRD).

The Preparation layer for the mural painting showed a general increase of the aggregate in relation to plasters *s.s.* The consequent lack of shrinkage fissures (Fig. 11d) when compared to plaster *s.s.*, determines a general reduction of total porosity [70].

Morphological features of the bedding mortars are very similar to those described for the scratch coats (Fig. 11e). These materials often show the occurrence of lumps in the matrix, that are widely fissured and darker than the binder (Fig. 11e). These latter derived from an advanced and localized pozzolanic reaction between the lime and fine glassy particles. In fact, the EDS analysis provided results compatible with the products of a pozzolanic reaction, such as C-S-H and/or C-A-H (Fig. 13) [4].

5. Discussion

Crucial information emerging from the characterisation of the mortar-based material from Villa San Marco is: type and provenance of the raw materials and how they were managed by the skilled workers to obtain the best technological features.

5.1. Raw materials

The raw materials could be basically referred to limestones and different volcanic deposits along with some accessory materials such as *cocciopesto*.

Limestones were used either as a lime-based binder in the mortar and plasters or as aggregate grains. Moreover, cut limestone *tesserae* were implemented for white geometrical decorations in the mosaic floors.

Despite the lack of specific provenance markers, mesozoic limestones from the Lattari Mountains (Fig. 1) were probably the source of carbonates for the mortar-based materials of the ancient *villae* of *Stabiae*, as deduced by the proximity of the outcrops; the same hypothesis was supported by Piovesan et al., [17] regarding the carbonate raw material from the Temple of Venus.

The other important materials of the mixtures have a volcanic origin. The aggregate of the innermost layers of plasters (the scratch coat and the *arriccio*) and the bedding mortars were constituted by volcanics, mainly minerals and glassy components (pumices and scoriae). The source of such sand can be ascribed to the southern Bay of Naples where the Somma-Vesuvius fingerprint can be easily recognised. This fingerprint mostly consists in the occurrence of leucite that characterises the undersaturated and potassium-rich volcanic rocks of Somma-Vesuvius [27,71]. Pumice enhanced the pozzolanic effects and, in some instances, *cocciopesto* was also added to enhance the same activity. The volcanic products of the Somma-Vesuvius volcano also provided the black stones (tephritic lavas) used along with white limestone as *tesserae* in the mosaics of villa S. Marco.

The right mixing between almost pure lime and *pozzolana* gave hydraulic properties to mortar-based materials, indicating how the ancient skilled workers were aware of the technical properties of these materials [5,11–13,17,37]. The utilisation of glass-rich pyroclastic deposits and ceramic fragments in order to strengthen the performances of the mortar-based material was a technological skill widely used during the Roman period. Particularly interesting is the case of *pulvis puteolanus* cited in Vitruvius's treatise De Archi-

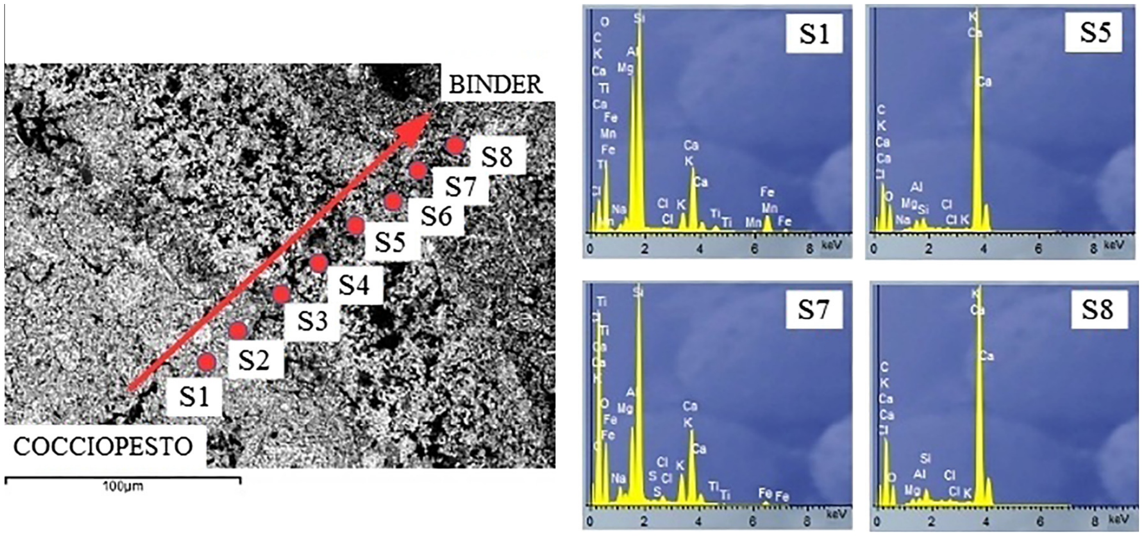

Fig. 11. SEM microphotographs: a) intra-particle porosity of pumice in the scratch coat SM 17-0; b) rounded pores in the *arriccio* SM 12-1; c) shrinkage fissures in plaster *s.s.* SM 16-2; d) preparation layer in sample SM 16-3; e) reaction lumps in bedding mortars SM 42; f) microporosity in the matrix of sample SM 17-0.

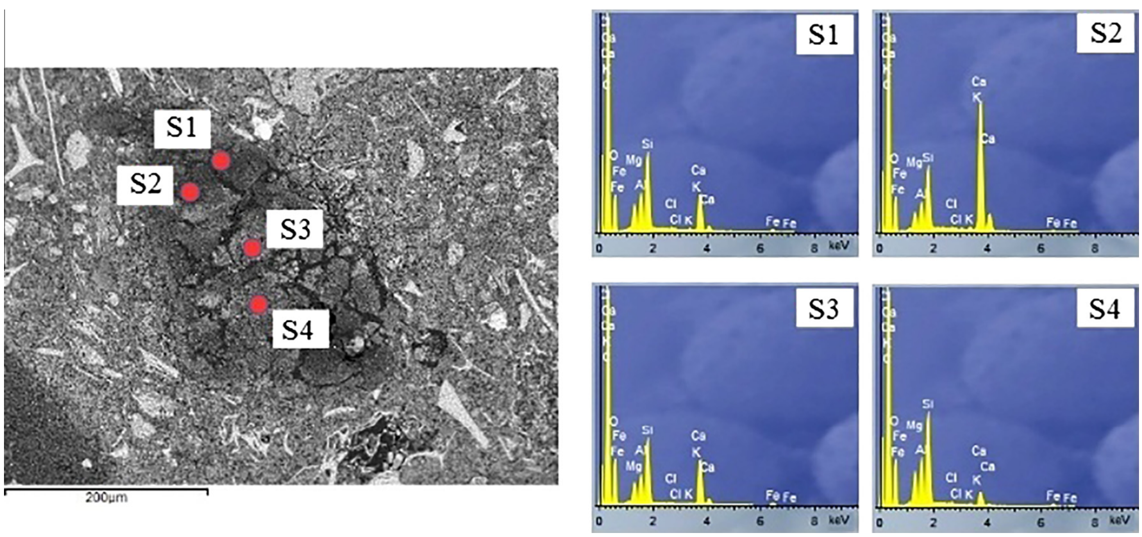

Fig. 12. SEM image and EDS spectra along the reaction rim between the ceramic fragments and the binder in a scratch coat SM 12-0.

tectura used for ancient seawater concretes and deriving from the pyroclastic activity of the *Campi Flegrei* [52,72]. A volcanic aggregate in fact, frequently occurs in the mortar-based materials of the Campania region, both in coastal areas (e.g. the Bay of Naples) and in inland Apennine areas, thanks to the availability and diffusion of pyroclastic deposits (both fall deposits and ignimbrites).

The ancient cities of Pompeii and Herculaneum offer a wide range of examples, since several private and public buildings have been investigated such as, the Temple of Venus [17], The *Garum* Shop [12], Casa di Pansa, Casa 17 [13] (Pompeii) and Villa dei Papiri (Herculaneum) [73].

As far as the volcanic aggregate is concerned, the mortar-based materials were made using a recipe of lime and volcanics, both available in the Vesuvius-environs. The latter are mostly constituted by leucite and leucite-bearing scoriae. In the aforementioned examples, the pozzolanic behaviour was also supported by the presence of *cocciopesto*.

In the northern part of the Bay of Naples, examples from the *Campi Flegrei* [74,75] also highlighted the presence of volcanic grains that are likely linked to the trachitic volcanic activity in this area [51]. The use of ignimbrite fragments, namely Neapolitan Yellow Tuff with the typical mineralogical association phillipsite-chabazite-analcime, is reported in the hydraulic mortars from the *Piscina Mirabilis* and the Thermal Complex of Baia in the Phlegraean area [74,75]. Lastly, since the explosive activity of volcanoes from Neapolitan district emplaced fall deposits in the internal area of the Campania region, the addition of pozzolanic-materials has been hypothesised also for the mortars of the Roman Theatre and Trajan's Arch in Benevento [76].

5.2. Technology of mortar based-materials

The obtained data allowed us to understand that the plasters of Villa San Marco were prepared following the typical enforcement techniques of the skilled workers during the Roman Age [77]. Those techniques were based on a multi-layer covering formed by a scratch coat, *arriccio*, plasters *s.s.* and a thin preparation layer for the mural painting. Each level of plaster was specifically designed to meet the best construction requirements.

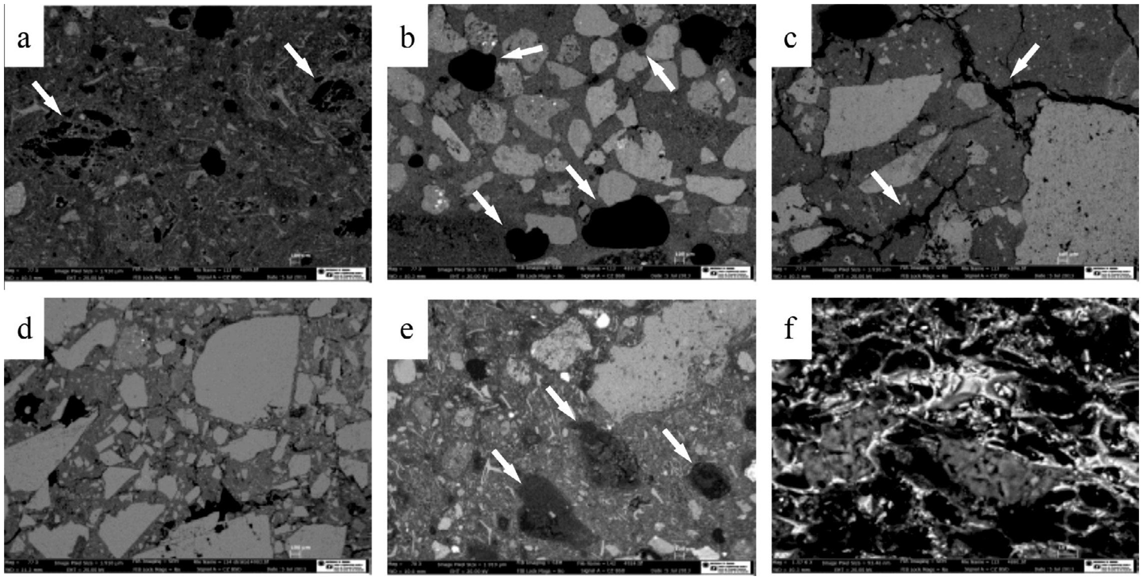

Fig. 13. SEM image and EDS spectra of a reaction lump in the bedding mortar SM 42.

For example, the scratch coat layer was a lime mortar made with a pozzolanic aggregate (mainly pumice and volcanic glass shards) and ceramic fragments (*cocciopesto*), with a binder-to-aggregate ratio between 0.92 and 1.27. The pozzolana-based raw material was used to promote a rapid setting of the mortar and to improve its adhesion to the wall.

The *arriccio* layer was a lime mortar where the volcanic aggregate (B/A between 0.67 and 1.70) is mostly composed of silicate crystals rather than *pozzolana* and/or *cocciopesto,* as highlighted by OM and QPXRD analyses. The quantitative approach on the XRD spectra detected a LO-AP content generally lower than those measured in the scratch coats (Table 2 and Table 3).

The medium-high values of the circularity and roundness of the grains, medium-high sorting and an adequate B/A ratio, conferred to the *arriccio* layers a high workability, allowing a vertical and planar correction of the rough surfaces of the scratch coat layer.

The scratch coats and *arriccio* layers showed some lumps, which provided other important information regarding the workmanship of mortar-based materials. These lumps may represent defects related to the preparation of the lime and appear in the form of inclusions of underburnt material or hardburnt particles [15]. On the other hand, the lumps can be related to the mixing procedures of the mortar components (unmixed lumps). The lime inclusions in the mortar-based materials of Villa San Marco are most probably unmixed lumps, as they showed the same optical features of the matrix (e.g. colour, texture). The occurrence of the unmixed lumps can also be related to the use of pozzolanic raw material that can promote an incomplete mixing of ingredients by reducing the processing time of fresh lime mortar.

Another hypothesis is that craftsmen could have preferred to not prolong the mixing time, in order to avoid an air excess in the mix, which could have deteriorated the mechanical performances and durability of the mortars [15].

The plasters *s.s.* were lime mortars with a calcite aggregate and a B/A ratio value between 1.38 and 4.26. The low value of the circularity and roundness of the grains suggests that the aggregate derived from crushed limestones. The low amount of aggregate most probably promoted the development of the shrinkage fissures during the curing and hardening stages of the mortar. As a consequence, the cohesion between the grains and binder may decrease. Plaster *s.s.* represented a supporting medium for the mural painting and was coated by a thin preparation layer composed of a lime mortar with a carbonate aggregate, but with a lower B/A ratio (from 1.17 to 1.70) and a sub-angular and moderately sorted aggregate. These textural features, along with the lower values of GSD, ranging from fine silt to very coarse sands, with the highest density in the range of the coarse sand, conferred a low porosity to the preparation layer, preventing the absorption of pigments from the mural painting by the underlying more porous support (plaster *s.s.*).

Mural paintings were realised as frescoes, often coated by a thin varnish layer in order to preserve the painting and to enhance its colours (*encaustication*). Any failures during the execution of the fresco were resolved simply by removing the preparation layer or even the plaster *s.s.*; this is the reason why plaster *s.s.* generally manifested a low cohesion. A calcite-bearing aggregate in the external layers also formed a white and neutral base for the pigments.

The bedding mortars of Villa San Marco were lime mortars made with a pozzolanic lightweight aggregate (mainly pumice and volcanic glass shards) and *cocciopesto* (never exceeding 2%), with a binder-to-aggregate ratio between 0.89 and 1.50 (Table 2).

Once again the presence of a pozzolanic raw material is higher than the silicate crystals, thus promoting a rapid setting of the mortar and a better mechanical performance after hardening, that was necessary to ensure the bedding of the structural elements of the masonry. It is worth noting that the occurrence of some organic admixtures (frustules) in sample SM 40 were most probably used to improve the cohesion and flexibility of the mortar.

The mosaic floors were also made with a multi-layer technology. Starting from the bottom, the floors were composed of two levels of mortar-based preparations, named *rudus* and *nucleus*, and a coating in *opera musiva* made of *lapidee tesserae* bedded with a thin layer of lime (*supranucleus*).

The *Rudera* and *nuclei* were lime mortars with volcanic sand and abundant *cocciopesto*, with a B/A ratio value between 1.10 and 2.45. *Cocciopesto* was also used to obtain a harder mortar-based material that better supported the compressive and dynamic stresses usually affecting a floor. The *Nucleus* presented a minor content of an aggregate when compared to the *rudus*. This feature provided a better workability of the fresh mortar allowing, during the enforcement of the *nucleus*, a horizontal and planar correction of the rough surface of the *rudus*. Both the *rudera* and *nuclei* presented the occurrence of unmixed lumps: the local absence of an aggregate in the unmixed lumps caused shrinkage fissures (Fig. 10a) due to a localized volumetric destabilization.*Supranuclei* were only made of lime, although sporadic volcanic sand, generally located between the mosaic *tesserae* of sample SM 30, was also found. The addition of volcanic sand was probably used to prevent a volumetric contraction during the curing of the mortar and the consequent formation of shrinkage fissures that could extend to the interfacial zone between the *supranucleus* and the *tesserae*.

The technological features of the plasters, bedding mortars and mortar-based preparation layers of the mosaic floors from Villa San Marco, here reported, find a good comparison with the Temple of Venus in *Pompeii* [17]. There, the authors recognised a multilayer technology of plasters (scratch coat > *arriccio* > *intonaco* > preparation) and floors, where each layer offered a precise support to the wall painting. Moreover, *cocciopesto* represented the favourite aggregate for the preparation of mosaic floors as noted in Villa San Marco. As far as the technological skills of the Pompeian workers are concerned, Piovesan et al. [17] assigned some properties of the plasters, such as the changes in GSD among the same mortars from the same stratigraphic unit or the occurrence of frequent lumps, to poor attention in the preparation of the plasters or poorly specialised workers.

On the other hand, the plasters from *Villa dei Papiri* in *Herculaneum* [73] are formed by only two distinct layers: the inner layer is made up of a carbonate binder and a volcanic aggregate, while in the outer layer, both the binder and the aggregate are carbonate. A finishing layer gave brightness and lustre to wall paintings.

Nevertheless, a multilayer plasters building technique, common to all important monuments, can be asserted, addressing a standard working practice among the skilled workers, in terms of technology as well as raw materials.

No evidence of this multilayer technology has been reported for the plasters from the *Garum* Shop in *Pompeii* [12]. The authors described only one sample with two layers distinguished by the presence of *cocciopesto* in the external layer. This can be due to the lower artistic value of the masonries, not decorated by frescoes.

Finally, along with the broad composition of the aggregate and the binder of the joint mortars samples from different archaeological sites in the Vesuvius-environs [12,13,17], a quite homogeneous B/A ratio (ranging from 1 to 1.5) can be also observed, again testifying precise and standardised technological choices.

6. Conclusions

This current research permitted a first minero-petrographic characterisation of the raw materials used to produce the mortar-based materials from Villa San Marco. They were classified according to the type of the binder and aggregate. Furthermore, the whole data set permitted a reconstruction of the ancient techniques implemented for the realization of these mortar-based materials, focusing on the ability of the ancient skilled workers.

Building materials used in ancient *Stabiae* architecture most probably had a local provenance, and are consistent with the surrounding geological setting. In fact, both the pozzolanic materials such as pumice and crystals (clinopyroxene, feldspar and accessories) compose volcanic beach sands and scoriae deposits [27] deriving from the degradation of the effusive igneous rocks from the Somma-Vesuvius volcano, as inferred by the mineralogical composition. Pumice and other volcanic glasses were added as a natural pozzolanic aggregate for the bedding and rendering mortars and are more abundant in the scratch coat and mortars; crystals, on the other hand, form the aggregate of the *arriccio* layers and plasters *s.s*.

It is hypothesized that a coarse crystal-rich fraction and a finer glassy/pumice-rich fraction, could have been easily separated by sieving a volcanic sand, thus providing the two products in different sizes and shapes [17,78].

The finer grain size was most probably constituted by the glassy component of the sediment (fine pumice and glass shards which promoted the high pozzolanic reactivity of the scratch coat layers and the bedding mortars; a further addition of *cocciopesto* even improved the pozzolanic aptitude of the mortar. In contrast, a less reactive and coarser fraction, mainly constituted by crystals was used as an aggregate in the lime-based mortars (*arriccio* layers).

These findings demonstrate a high level of specialization on the part of the workers and artists involved in the construction of Villa San Marco and the other maritime villas of *Stabiae,* as well as a high level of knowledge of the properties of the raw materials used. These raw materials were accurately selected in order to create a high quality and artistic product, as testified by the implemented refined techniques and the durability of the artefacts.

The comparison with published research on mortar-based materials from other sites of the Vesuvius-environs confirmed a wide utilisation of local raw materials. Furthermore, a multilayer technology of plasters seems to have been adopted for valuable or monumental buildings, as in the case of the patrician *otium* villas of *Stabiae* or the Temple of Venus in *Pompeii*. On the contrary, a rough and fast technology (only two layers) was adopted for common buildings (e.g. the *Garum* Shop) [12,13].

This research contributes to the knowledge and understanding of the technical, artistic and architectural skills achieved during Roman times. It may represent a valuable reference for the future restoration of Villa San Marco masonries that, despite their quite good state of conservation, are prone to an on-going decay due to weathering as well as the presence of tourists in the archaeological area of ancient *Stabiae*.

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References

[1] A. Morricone, A. Macchia, L. Campanella, M. David, S. de Togni, M. Turci, A. Maras, C. Meucci, S. Ronca, Archeometrical analysis for the characterization of mortars from Ostia Antica, Proc. Chem. 8 (2013) 231–238.

[2] J. Elsen, Microscopy of historical mortars – a review, Cement Concrete Res. 36 (2006) 1416–1424.

[3] J. Elsen, K. Van Balen, G. Mertens, Hydraulicity in Historic Lime Mortars: A Review, 2nd Historic Mortars Conference HMC2010 and RILEM TC 203-RHM Final Workshop 22–24 September, Prague, Czech Republic, 2010, pp. 45–129.

[4] L. Bertolini, Materiali da costruzione, Struttura, proprietà e tecnologie di produzione. De Agostini ed., Vol. I, 2010. XI–449.

[5] C.M. Belfiore, G.V. Fichera, M.F. La Russa, D. Barca, G. Galli, S.A. Ruffolo, A. Pezzino, A multidisciplinary approach for the archaeometric study of pozzolanic aggregate in roman mortars: the case of villa dei quintili Rome, Italy, Archaeometry 57 (2015) 269–296.

[6] R. Piovesan, M.C. Dalconi, L. Maritan, C. Mazzoli, X-rays powder diffraction clustering and quantitative phase analysis on historical mortars, Eur. J. Mineral. 25 (2013) 165–175.

[7] R. Piovesan, R. Siddall, C. Mazzoli, L. Nodari, The Temple of Venus (Pompeii): a study of the pigments and painting techniques, J. Archaeol. Sci. 38 (2011) 2633–2643.

[8] C. Boschetti, C. Leonelli, M. Macchiarola, P. Veronesi, A. Corradi, C. Sada, Early evidences of vitreous materials in Roman mosaics from Italy: an archaeological and archaeometric integrated study, J. Cult. Herit. 9 (2008) 21–26.

[9] A. Moropoulou, A. Bakolas, S. Anagnostopoulou, Composite Materials in ancient structures, Cement Concrete Comp. 27 (2005) 295–300.

[10] M. Lezzerini, S. Legnaioli, G. Lorenzetti, V. Palleschi, M. Tamponi, Characterization of historical mortars from the bell tower of St. Nicholas church (Pisa, Italy), Constr. Build. Mater. 69 (2014) 203–212.

[11] G.V. Fichera, C.M. Belfiore, M.F. La Russa, S.A. Ruffolo, D. Barca, R. Frontoni, G. Galli, A. Pezzino, Limestone provenance in Roman lime-volcanic ash mortars from the Villa dei Quintili, Rome, Geoarchaeology 30 (2015) 79–99.

[12] R. De Luca, D. Miriello, A. Pecci, S. Domìnguez-Bella, D. Bernal-Casasola, D. Cottica, A. Bloise, G.M. Crisci, Archaeometric study of mortars from the garum shop at Pompeii, Campania, Italy, Geoarchaeology 30 (2015) 330–351.

[13] D. Miriello, D. Barca, A. Bloise, A. Ciarallo, G.M. Crisci, T. De Rose, C. Gattuso, F. Gazineo, M.F. La Russa, Characterisation of archaeological mortars from Pompeii (Campania, Italy) and identification of construction phases by compositional data analysis, J. Archaeol. Sci. 37 (2010) 2207–2223.

[14] C. Lubritto, M. Caroselli, S. Lugli, F. Marzaioli, S. Nonni, S. Marchetti Dori, F. Terrasi, AMS radiocarbon dating of mortar: the case study of the medieval UNESCO site of Modena, Nucl. Instrum. Meth. B 361 (2015) 614–619.

[15] J.P. Ingham, Geomaterials Under the Microscope, a Colour Guide, Manson Publishing Ltd, London, 2013.

[16] R. Piovesan, C. Mazzoli, L. Maritan, P. Cornale, Fresco and Lime-paint: an experimental study and objective criteria for distinguishing between these painting techniques, Archaeometry 54 (2012) 723–736.

[17] R. Piovesan, E. Curti, C. Grifa, L. Maritan, C. Mazzoli, Ancient plaster technology: petrographic and microstratigraphic analysis of plaster-based building materials from the Temple of Venus, Pompeii, in: P.S. Quinn (Ed.), Interpreting Silent Artefacts: Petrographic Approaches to Archaeological Ceramics, Archaeopress, Oxford, 2009, pp. 65–79.

[18] M.S. Abu Aysheh, Studio archeometrico-tecnologico e conservazione dei mosaici romani del sito archeologico di Suasa (PhD Thesis), Alma Mater Studiorum – Università di Bologna, 2008. 177.

[19] J. Alvares Galindo, E. Ontiveros Ortega, Morteros, in: E. Ontiveros Ortega (Ed.), PH cuadernos – Programa de normalización de estudios previos aplicado a bienes inmuebles, Junta de Andalucía. Consejería de Cultura. Instituto Andaluz del Patrimonio Histórico, 2006, pp. 93–145.

[20] O. Cazalla Vázquez, M.J. de la Torre López, Morteros de restauración y morteros antiguos. Técnicas de estudio, in: R. Villegas Sánchez, E. Sebastián Pardo (Eds.), Metodología de diagnóstico y evaluación de tratamiento para la conservación de los edificios históricos, Cuadenos PH, Junta de Andalucía, Consejería de Cultura, Instituto Andaluz del Patrimonio Histórico y Editorial Comares, 2003, pp. 36–47.

[21] A. Arizzi, H. Viles, G. Cultrone, Experimental testing of the durability of lime-based mortars used for rendering historic buildings, Constr. Build. Mater. 28 (2012) 807–818.

[22] A. Arizzi, G. Cultrone, Aerial lime-based mortars blended with a pozzolanic additive and different admixtures: A mineralogical, textural and physical-mechanical study, Constr. Build. Mater. 31 (2012) 135–143.

[23] A. Arizzi, J. Martínez, G. Cultrone, D. Benavente, Mechanical evolution of lime mortars during the carbonation process, Key Eng. Mat. 465 (2011) 483–486.

[24] G. Cultrone, A. Arizzi, E. Sebastián, C. Rodriguez-Navarro, Sulfation of calcitic and dolomitic lime mortars in the presence of diesel particulate matter, Environ. Geol. 56 (3–4) (2008) 741–752.

[25] C. Rodríguez-Navarro, E. Ruiz Agudo, M. Ortega-Huertas, E. Hansen, Nanostructure and irreversible colloidal behaviour of $Ca(OH)_2$: implication in Cultural Heritage Conservation, Langmuir 21 (2005) 10948–10957.

[26] K. Elert, C. Rodriguez-Navarro, E. Sebastian Pardo, E. Hansen, O. Cazalla, Lime mortars for the conservation of historic buildings, Stud. Conserv. 47 (1) (2002) 62–75.

[27] V. Morra, A. De Bonis, C. Grifa, A. Langella, L. Cavassa, R. Piovesan, Minero-petrographic study of cooking ware and pompeian red ware (rosso pompeiano) from Cuma (southern Italy), Archaeometry 55 (5) (2013) 852–879.

[28] C. Grifa, A. De Bonis, V. Guarino, C.M. Petrone, C. Germinario, M. Mercurio, G. Soricelli, A. Langella, V. Morra, Thin walled pottery from Alife (Northern Campania, Italy), Period. Mineral. Special Issue EMAC 2013 84 (1) (2015).

[29] C. Grifa, A. De Bonis, A. Langella, M. Mercurio, G. Soricelli, V. Morra, A Late Roman ceramic production from Pompeii, J. Archaeol. Sci. 40 (2013) 810–826.

[30] C. Grifa, G. Cultrone, A. Langella, M. Mercurio, A. De Bonis, E. Sebastián, V. Morra, Ceramic replicas of archaeological artefacts in Benevento area (Italy): petrophysical changes induced by different proportions of clays and temper, Appl. Clay Sci. 46 (3) (2009) 231–240.

[31] C. Grifa, V. Morra, A. Langella, P. Munzi, Byzantine ceramic productions from Cuma (Campi Flegrei, Napoli), Archaeometry 51 (1) (2009) 75–94.

[32] C. Grifa, V. Morra, A. Langella, G. Cultrone, E. Sebastián, Technological features of glazed Protomajolica Ware from Benevento (Italy), in: R. Fort, M. Alvarez de Buergo, M. Gomez Heras, C. Vasquez-Calvo (Eds.), Heritage, Weathering and Conservation, Taylor & Francis, Balkema, 2006, pp. 123–135.

[33] C. Grifa, A. Langella, V. Morra, G. Soricelli, Pantellerian Ware from Miseno (Campi Flegrei, Napoli), Period. Mineral. 74 (1) (2005) 69–86.

[34] A. De Bonis, G. Cultrone, C. Grifa, A. Langella, V. Morra, Clays from the Bay of Naples (Italy): new insight on ancient and traditional ceramics, J. Eur. Ceram. Soc. 34 (13) (2014) 3229–3244.

[35] A. De Bonis, C. Grifa, G. Cultrone, P. De Vita, A. Langella, V. Morra, Raw materials for archaeological pottery from the Campania Region of Italy: a petrophysical characterization, Geoarchaeology 28 (5) (2013) 478–503.

[36] A. De Bonis, C. Grifa, A. Langella, M. Mercurio, M.L. Perrone, V. Morra, Archaeometric study of roman pottery from Caudium area (Southern Italy), Period. Mineral. 79 (2) (2010) 73–89.

[37] C. Germinario, G. Cultrone, F. Izzo, A. Langella, M. Mercurio, V. Morra, A. Santoriello, S. Siano, L. Tomay, C. Grifa, Archaeometric characterization of common wares from Ancient Appia Landscapes Survey (Benevento-Italy): new elements to reconstruct a Late Roman micro-regional ceramic production, in: Conference proceedings of 1st International Conference on Metrology for Archaeology, Benevento, Italy, October, 22–23, 2015, pp. 561–565.

[38] V. Guarino, A. De Bonis, C. Grifa, A. Langella, V. Morra, L. Pedroni, Archaeometric study on terra sigillata from Cales (Italy), Period. Mineral. 80 (3) (2011) 455–470.

[39] M.F. La Russa, S.A. Ruffolo, M. Ricca, N. Rovella, V. Comite, M. Alvarez de Buergo, D. Barca, G.M. Crisci, Archaeometric approach for the study of mortars from the underwater archaeological site of Baia (Naples) Italy: Preliminary results, Period. Mineral. 3 (2015) 553–567.

[40] M. Ricca, M.F. La Russa, S.A. Ruffolo, B. Davidde, D. Barca, G.M. Crisci, Mosaic marble tesserae from the underwater archaeological site of Baia (Naples, Italy): determination of the provenance, Eur. J. Mineral. 26 (2014) 323–331.

[41] M. Ricca, C.M. Belfiore, S.A. Ruffolo, D. Barca, M. Alvarez De Buergo, G.M. Criscia, M.F. La Russa, Multi-analytical approach applied to the provenance study of marbles used as covering slabs in the archaeological submerged site of Baia (Naples, Italy): the case of the "Villa con ingresso a protiro", Appl. Surf. Sci. 357 (2015) 1369–1379.

[42] A. De Bonis, S. Febbraro, C. Germinario, D. Giampaola, C. Grifa, V. Guarino, A. Langella, V. Morra, Distinctive volcanic material for the production of campana a ware: the workshop area of neapolis at the duomo metro station in Naples, Italy, Geoarchaeology (2016), http://dx.doi.org/10.1002/gea.21571.

[43] V. Guarino, A. De Bonis, I. Faga, D. Giampaola, C. Grifa, A. Langella, V. Liuzza, R. Pierobon Benoit, P. Romano, V. Morra, Production and circulation of thin walled pottery from the Roman port of Neapolis, Campania (Italy), Period. Mineral. 85 (2016) 95–114.

[44] A. Marturano, G. Aiello, D. Barra, L. Fedele, C. Grifa, V. Morra, R. Berg, A. Varone, Evidence for Holocenic uplift at Somma-Vesuvius, J. Volcanol. Geoth. Res. 184 (2009) 451–461.

[45] F. Russo, A. Valente, L'impatto delle eruzioni tardo oloceniche del Somma-Vesuvio sul paesaggio e le attività umane. Una sintesi di dati geoarcheologici, Boll. Soc. Geograf. 13 (3) (2010) 583–604.

[46] F. Russo, I siti archeologici del Bronzo Antico in Campania interessata dall'eruzioni vesuviana delle "Pomici di Avellino": elementi geomorfologici e stratigrafici, in: C. Albore Livadie (Ed.), L'eruzione vesuviana delle "Pomici di Avellino" e la facies di Palma Campania (Bronzo Antico), 2, Edipuglia, Bari, 1999, pp. 93–118.

[47] C. Albore Livadie, L. Campajola, A. D'Onofrio, R.K. Moniot, V. Roca, M. Romano, F. Russo, F. Terrasi, Evidence of the adverse impact of the "Avellino Pumices" Eruption of Somma –Vesuvio on Old Bronze Age Sites in the Campanian Region (Southern Italy), Quaternaire 9 (1) (1998) 37–43.

[48] F. Russo, M. Valletta, Rischio ed impatto ambientale: considerazioni e precisazioni, Ital. J. Sci. 112 (1993) 103–126.

[49] L. Fedele, C. Scarpati, M. Lanphere, L. Melluso, V. Morra, A. Perrotta, G. Ricci, The Breccia Museo formation, Campi Flegrei, southern Italy: geochronology, chemostratigraphy and relationship with the Campanian Ignimbrite eruption, B. Volcanol. 70 (2008) 1189–1219.

[50] P. Cappelletti, G. Cerri, A. Colella, M. de'Gennaro, A. Langella, A. Perrotta, C. Scarpati, Post-eruptive processes in the Campanian Ignimbrite, Miner. Petrol. 79 (1–2) (2003) 79–97.

[51] A. Langella, D.L. Bish, P. Cappelletti, G. Cerri, A. Colella, R. de Gennaro, S.F. Graziano, A. Perrotta, C. Scarpati, M. de Gennaro, New insights into the mineralogical facies distribution of Campanian Ignimbrite, a relevant Italian industrial material, Appl. Clay Sci. 72 (2013) 55–73.

[52] M. de'Gennaro, P. Cappelletti, A. Langella, A. Perrotta, C. Scarpati, Genesis of zeolites in the Neapolitan Yellow Tuff: geological, volcanological and mineralogical evidence, Contrib. Mineral. Petr. 139 (2000) 17–35.

[53] R. Cioni, L. Civetta, P. Marianelli, N. Metrich, R. Santacroce, A. Sbrana, Compositional Layering and Syn-eruptive Mixing of a Periodically Refilled Shallow Magma Chamber: the AD 79 Plinian Eruption of Vesuvius, J. Petrol. 36 (1995) 739–776.

[54] D. Insinga, F. Molisso, C. Lubritto, M. Sacchi, I. Passariello, V. Morra, The proximal marine record of Somma-Vesuvius volcanic activity in the Naples and Salerno bays (eastern Tyrrhenian Sea) during the last 3 kyrs, J. Volcanol. Geoth. Res. 177 (2008) 170–186.

[55] M. Lanphere, D. Champion, L. Melluso, V. Morra, A. Perrotta, C. Scarpati, D. Tedesco, A. Calvert, 40Ar/39Ar ages of the AD 79 eruption of Vesuvius, Italy, B. Volcanol. 69 (2007) 259–263.
[56] G. Bonardi, B. D'Argenio, V. Perrone, Carta Geologica dell'Appennino meridionale in scala 1:250.000, Mem. Soc. Geol. It. 41 (1988) 1341.
[57] G. Di Maio, M. Pagano, Considerazioni sulla linea di costa e sulle modalità di seppellimento dell'antica Stabia a seguito dell'eruzione vesuviana del 79 d.C., Riv. Sc. Pr. 14 (2003) 197–245.
[58] P. Vitruvius, The Ten Books on Architecture translated by M.H. Morgan, Cambridge University Press, Cambridge, UK, 1914.
[59] UNI-EN 11305:2009, Cultural heritage. Historical mortars – Guideline for the mineralogical – petrographycal, physical and chemical characterization of mortar, CNR-ICR, Roma, 2009.
[60] UNI-EN 11176:2006, Cultural heritage. Petrographic description of a mortar, CNR-ICR, Roma, 2006.
[61] C.K. Wentworth, A scale of grade and class terms for clastic sediments, J. Geol. 30 (5) (1922) 377–392.
[62] W.C. Krumbein, L.L. Sloss, Stratigraphy and Sedimentation, second ed., Freeman & Co, San Francisco, 1963.
[63] R Development Team, R: a Language and Environment for Statistical Computing. R. Version 1.1.0 for Mac. R Foundation for Statistical Computing, Vienna, Austria, http://microarrays.unife.it/CRAN/, 2005.
[64] D.L. Bish, J.E. Post, Quantitative mineralogical analysis using the Rietveld full-pattern fitting method, Am. Mineral. 78 (1993) 932–940.
[65] F.H. Chung, Quantitative interpretation of X-ray diffraction patterns of mixtures. I. Matrix-flushing method of quantitative multicomponent analysis, J. Appl. Crystallogr. 7 (1974) 519–525.
[66] A.F. Gualtieri, A. Tartaglia, Thermal decomposition of asbestos and recycling in traditional ceramics, J. Eur. Ceram. Soc. 20 (2000) 1409–1418.
[67] International Crystal Structure Database (ICSD), 2010. ICSD CD-Rom. FIZ Karlsruhe. National Institute of Standards and Technology (NIST). PC version Release 2010/2.
[68] D.L. Whitney, B.W. Evans, Abbreviations for names of rock-forming minerals, Am. Mineral. 95 (2010) 185–187.
[69] NORMAL 1/88, Alterazioni macroscopiche dei Materiali Lapidei: Lessico, CNR-ICR, Roma, 1988.
[70] I. Papayianni, M. Stefanidou, Strength–porosity relationships in lime–pozzolan mortars, Constr. Build. Mat. 20 (2006) 700–705.
[71] L. Buffone, S. Lorenzoni, M. Pallara, E. Zanettin, The millstones of ancient pompei: a petro-archaeometric study, Eur. J. Mineral. 15 (1) (2003) 207–215.
[72] C. Stanislao, C. Rispoli, G. Vola, P. Cappelletti, V. Morra, M. de' Gennaro, Contribution to the knowledge of ancient Roman seawater concretes: Phlegrean pozzolan adopted in the construction of the harbour at Soli-Pompeiopolis (Mersin, Turkey), Period. Mineral. 80 (3) (2011) 471–488.
[73] M.L. Amadori, S. Barcelli, G. Poldi, F. Ferrucci, A. Andreottic, P. Baraldi, M.P. Colombini, Invasive and non-invasive analyses for knowledge and conservation of Roman wall paintings of the Villa of the Papyri in Herculaneum, Microchem. J. 118 (2015) 183–192.
[74] C. Rispoli, R. Esposito, A. De Bonis, P. Cappelletti, V. Morra, P. Talamo, The Thermal Complex of Baia: preliminary characterizationof mortars, in: Un ponte tra arte e scienza: passato, presente e prospettive future. Arcavacata di Rende (CS), 9-11 marzo 2016, AIAr – Associazione Italiana di Archeometria, 2016, p. 87.
[75] C. Rispoli, S.F. Graziano, A. De Bonis, P. Cappelletti, R. Esposito, P. Talamo, Piscina Mirabilis: characterization of geomaterials, in: Proceedings of the 1st International Conference on Metrology for Archaeology. Benevento, 22-23 ottobre 2015, 2015, pp. 266–270.
[76] F. Izzo, C. Germinario, C. Grifa, M. Mercurio, D. Spatuzzi, L. Tomay, A. Langella, Simultaneous Thermal Analyses and Fourier Transform Infrared Spectroscopy of ancient mortars from Arch of Trajan and Roman Theatre (Benevento, Italy), in: Conference proceedings of 1st International Conference on Metrology for Archaeology, Benevento, Italy, October, 22-23, 2015, pp. 240–245.
[77] A. Aveta, Materiali e tecniche tradizionali nel napoletano. Note per il restauro architettonico. Arte tipografica ed., Napoli, 1987.
[78] V. Morra, D. Calcaterra, P. Cappelletti, A. Colella, L. Fedele, R. de' Gennaro, A. Langella, M. Mercurio, M. de' Gennaro, Urban geology: Relationships between geological setting and architectural heritage of the Neapolitan area, in: M. Beltrando, A. Peccerillo, M. Mattei, S. Conticelli, C. Doglioni (Eds.), The geology of Italy: Tectonics and life along plate margins, Journal of the Virtual Explorer, vol. 36, 2010, pp. 1–59.