

## Article

# Archaeometric Investigation of Artificial Stone Materials from the *Theatrum Marcelli* (Rome, Italy)

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**Abstract:** This study illustrates the results of minero-petrographic and microchemical investigations of artificial stone materials (mortars, plasters, and bricks) taken from the *Theatrum Marcelli* (Rome, Italy). To achieve this objective, the artificial building materials were analysed using Polarized Optical Microscopy (POM) and a Scanning Electron Microscope (SEM) used in backscattered electron (BSE) mode and coupled with an Energy-Dispersive Spectrometer (EDS) after a sampling campaign. The POM was aimed at collecting information on the textural and mineralogical characteristics of the samples (identification of the main minerals constituting the aggregate, grain size and shape, and the evaluation of the binder/aggregate ratio). The data also supported technological assessments through the characterization of the raw materials used for the manufacture of the mortars/plasters. Furthermore, the SEM-EDS investigations revealed the chemical composition of both the aggregate and the binder, which was useful for estimating their hydraulicity index (HI). The diagnostic campaign allowed us to obtain interesting information on the plasters/mortars used in the *Theatrum Marcelli*, together with their probable production technology. In particular, the raw materials were quite homogeneous, thus confirming the traditional methodology used in Roman times to create natural hydraulic mortars by the addition of pozzolanic volcanic material to aerial lime. The volcanic component of the aggregate seems to be compatible with the ultrapotassic products of the Roman Magmatic Province—likely with the *Pozzolane Rosse* pyroclastic deposit of the Alban Hills district.

**Keywords:** *Theatrum Marcelli*; hydraulic mortar; hydraulicity index; pozzolana; brick; plaster; Roman mortar technology; petrography analyses; SEM-EDS investigations



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## 1. Introduction

The use of construction materials in Roman architecture demonstrates extraordinary engineering ability, based on the knowledge and expertise of builders who reworked local materials to achieve durable complex stone and concrete masonry [1]. Monuments from the Republican era and the early Imperial period are the result of the skilful use of diverse volcanic deposits from the nearby Monti Sabatini and Colli Albani districts, as well as travertine quarried near Tivoli [2].

The employment of different materials reflects the progressive technological evolution that, over time, allowed increasingly complex and refined engineering solutions.

Archaeological evidence indicates that the earliest Republican monuments in Rome were constructed using the soft volcanic tuffs immediately available locally on Palatine Hill. It was only from the 1st century BCE, with the acquisition of nearby territories, that more durable and well-lithified tuffs, sourced from the Monti Sabatini and Albani volcanic districts, were quarried to obtain dimension stone for *opus quadratum* masonries. Travertine blocks decorated the tuff walls as keystones, capitals, or facing slabs, as seen in the Forum of Caesar (46 BCE) [3,4]. By the late Republican period, Roman builders introduced a significant technological shift. Walls began to be constructed with a concrete core (*opus caementicium*) and were faced with tuff blocks arranged in irregular and geometric patterns (*opus incertum* and *opus reticulatum*, respectively) or fired bricks (*lateres cocti*), as in *opus testaceum*.

This technical know-how extended beyond the selection of cut stone elements, including advanced techniques for preparing pozzolanic mortars to enhance their strength and durability [5–9]. Scientific studies of Roman mortars reveal that in the early stages (beginning of the 2nd century BCE), they contained crushed tuff as fine and coarse aggregate, alongside less coherent pyroclastic deposits sourced from nearby outcrops close to construction sites. This suggests an initial lack of a standardized system for selecting pozzolanic materials, prioritizing proximity to extraction sites and ease of availability. It was from the late 2nd to early 1st century BCE that builders realized the potential of adding pozzolanic aggregates from specific altered facies to significantly improve the mechanical properties of mortars. From the Augustan age onwards, systematic selection became common, both in the construction of new complex buildings and in restoration interventions on older structures [10–13].

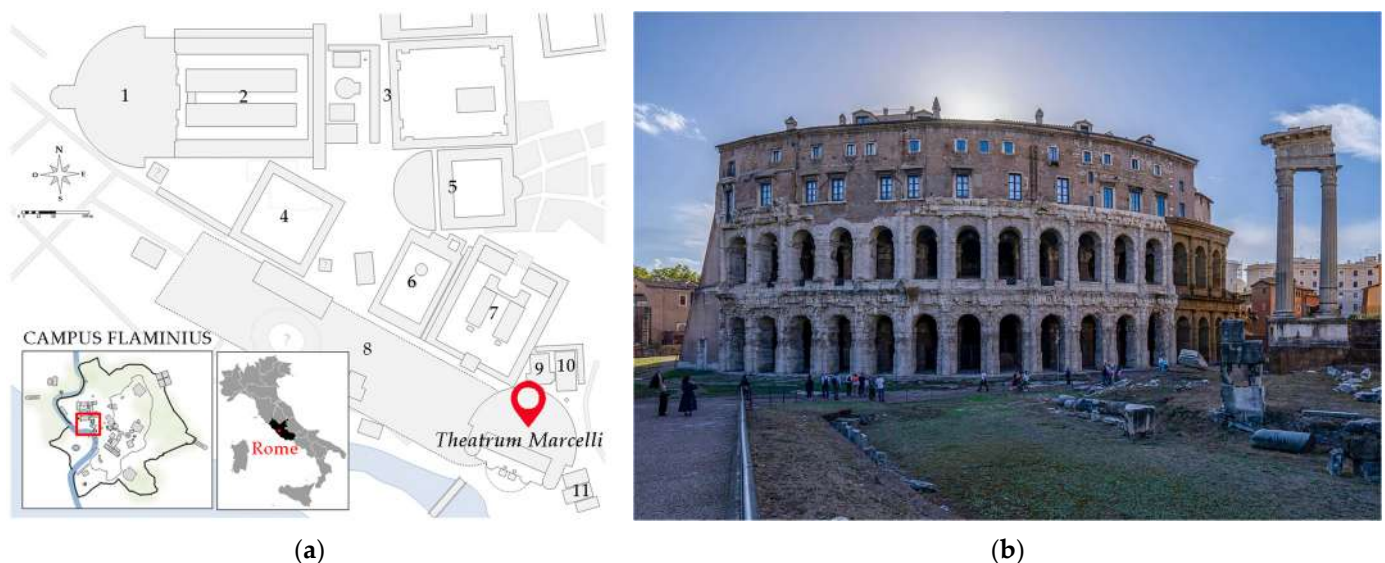
These findings are supported by ancient sources, particularly Vitruvius's *De Architectura*, written between 31 and 27 BCE, during the transition between the late Republican and early Imperial period. In his work, Vitruvius provides detailed documentation on how Republican builders carefully selected various volcanic and sedimentary stones available in the Roman region, taking into account their durability and stability under diverse environmental conditions. The builders' ability to adapt these materials to specific construction needs highlights a deep understanding of their physical and mechanical properties, supported by a combination of practical experience (*fabrica*) and theoretical reflection (*ratiocinatione*), a synthesis Vitruvius himself celebrates as "*scientia*" [14].

Thus, the builders of the late Republican era inherited and refined a wealth of skills rooted in meticulous observation, extensive practical experience, and innovative experimentation. This foundation enabled them to achieve remarkable technical advances that would come to define Roman imperial architecture. The need to innovate was also driven by constant environmental challenges, such as frequent floods of the Tiber, earthquakes, and fires, which required resilient architectural solutions [2,15–17]. Additionally, military conquests and the growing wealth of the Republic encouraged a culture of patronage and competition among the elite, who used monumental architecture to express their prestige. These dynamics led to a "race for innovation" in the design and execution of more complex buildings requiring increasingly advanced techniques.

The Theatre of Marcellus (30?–11 BCE) stands as one of the monuments embodying the technological advancements of the transition from the late Republican to the Imperial period, born from the fortune of Emperor Augustus's elaborate building and restoration program.

## 2. Historical Background and Building Materials of the *Theatrum Marcelli*

The *Theatrum Marcelli* was built by Emperor Augustus *ad aedem Apollonis* in the Campus Martius area, a site designated since the Republican period for theatrical *ludi* [18] (Figure 1).



**Figure 1.** (a) Map of *Campus Flaminius* area in Rome in which the *Theatrum Marcelli* (red square) and some other important monuments are located: *Theatrum Pompeii* (1); *Porticus Pompeii* (2); *Porticus Minucia* (3); *Porticus Octavia* (4); *Theatrum Balbi* and *Crypta Balbi* (5); *Porticus Philippi* (6); *Porticus Octaviae* (ex *Porticus Metelli*) (7); *Circus Flaminius* (8); *Temple of Apollo Medicus* (9); *Temples of Bellona* (10); *Temples of the Forum Holitorium* (11) (image modified and reproduced under Creative Commons Attribution-ShareAlike 4.0 International license—Cassius Ahenobarbus author ([https://it.wikipedia.org/wiki/Regio\\_IX\\_Circus\\_Flaminius#/media/File:Plan\\_champ\\_de\\_mars\\_sud.png](https://it.wikipedia.org/wiki/Regio_IX_Circus_Flaminius#/media/File:Plan_champ_de_mars_sud.png) (accessed on 25 November 2024)), “Plan champ de mars sud”). (b) Overall view of *Theatrum Marcelli* (image reproduced under Creative Commons Attribution-ShareAlike 4.0 International license—Fiat 500e author ([https://en.wikipedia.org/wiki/Theatre\\_of\\_Marcellus#/media/File:Teatro\\_di\\_Marcello\\_intero.jpg](https://en.wikipedia.org/wiki/Theatre_of_Marcellus#/media/File:Teatro_di_Marcello_intero.jpg) (accessed on 25 November 2024)), “Teatro di Marcello intero”).

It remains uncertain whether the theatre was constructed based on a pre-existing design by Julius Caesar. However, it is rather clear that Caesar initiated the preparation of the area, as he had planned to build a vast theatre sloping down from the *Rupe Tarpea* (*Theatrum summae magnitudinis Tarpeio monti accubans*) [19]. The area of the *Circus Flaminius*, designated for the theatre’s construction, was already densely populated and occupied by civil and religious buildings, including the *Circus Flaminius* itself, the *Porticus Metelli*, the *Temples of Apollo Medicus* and *Bellona*, and the temples of the *Forum Holitorium* (Figure 1a). For this reason, it was necessary to demolish a substantial portion of the existing structures, while the sacred buildings were either relocated or restored. An exception was made only for the *Temple of Pietas*, which was never rebuilt, a decision for which Caesar faced significant criticism [20].

Thus, the construction process can be divided into two distinct phases: the initial clearance of the area by Caesar, followed by the theatre’s erection under Augustus, who acquired additional private lands at his own expense [18].

Augustus, therefore, ordered the levelling and paving of the area, standardizing the elevation across the entire space between the *Porticus Octaviae* and the *Forum Holitorium*. Given that the new *Temple of Apollo Sosianus* and the *Porticus Octaviae* date between 30 and 20 BCE, and considering the chronological alignment with these structures, the *Theatrum Marcelli* may have been constructed within this same time frame [20]. The theatre was dedicated to the memory of Augustus’s nephew, Marcellus, the son of his sister Octavia and

husband of his daughter Julia, who had been destined for succession but died prematurely in 23 BCE [21]. In 17 BCE, the structure, likely still incomplete, hosted the *ludi seculares*, but the formal inauguration took place most probably in 13 BCE [21]. After Nero's fire and the battle of the Capitoline by Vitellius' forces in 69 CE, Vespasian restored the theatre's *scena*, and further renovations likely occurred under Alexander Severus [22], though additional details are scarce.

The theatre likely remained in use at least until the end of the 5th century CE. Despite some of the theatre travertine blocks being removed and used for the restoration of the *Pons Cestius* at the end of the 4th century, new statues were commissioned for the theatre in 421 CE by the prefect Petronius Maximus [23]. Over the centuries, however, the structure suffered from various modifications and natural disasters, such as earthquakes and Tiber floods, which caused the significant burial and collapse of some areas of the theatre [16,17].

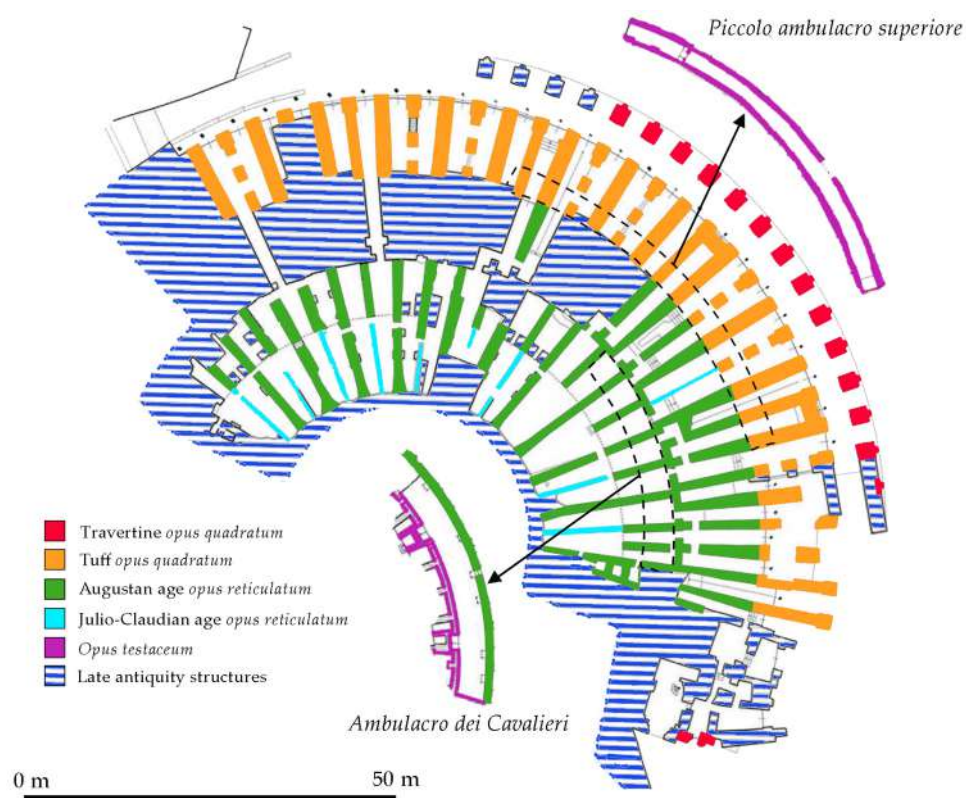
In the 12th century, the building came under the control of the Faffi family, who converted it into a fortified structure [24]. In the 16th century, the Savelli family transformed the theatre into a palace, based on a design by Baldassare Peruzzi, and it was later acquired by the Orsini in the 18th century. The theatre was finally cleared of additions in the 1920s when it was acquired by the City of Rome [20].

The *Theatrum Marcelli* is among the best-preserved ancient Roman theatres. Its design appears to have been conceived as a political and urban response to the older Theatre of Pompey [23]. The *Theatrum Marcelli* was the second largest in terms of size, with a capacity of about 20,550 *loca* (around 15,000 spectators) compared to the 17,580 seats of the Theatre of Pompey [25].

Today, elements of the original structure that remain identifiable include the facade with two of the three ambulae (Doric and Ionic), two internal galleries known as the "Knights' Gallery" (*ambulacro dei Cavalieri*), and the "Upper Small Ambulatory" (*piccolo ambulacro superiore*), which helped direct the flow of spectators within the building (Figures 1 and 2) [20]. There are also several internal rooms originally used as storage spaces and shops, along with elongated *fornici*. Due to the complexity of the structure, different construction techniques and materials were used to meet the architectural and structural requirements. Materials such as travertine and tuff were employed for the load-bearing sections, which were subjected to greater mechanical stress [20]. The facade was built in *opus quadratum* of travertine, while the counter-façade and parts of the radial walls were constructed with *opus quadratum* in *tuffo lionato*, incorporating travertine for the keystones and impost blocks. In contrast, the inner walls were made with *opus caementicium* and faced with *opus reticulatum* and bricks (*opus testaceum*). *Opus testaceum* was utilized exclusively for the internal semi-annular *ambulae*. Moreover, the walls of the *ambulacro dei Cavalieri* were constructed using two distinct techniques: the inner wall, adjacent to the orchestra, was faced with uniform yellow bricks, while the opposing wall was made with *opus reticulatum* (Figure 2) [26].

This paper aims to characterize the different building materials used in the construction of the *Theatrum Marcelli*. In particular, the layers of some plasters, mortars, and bricks taken from diverse areas of the monument are investigated. The purpose is to improve knowledge about the Roman construction techniques used for the production of artificial stone materials in the early years of the Empire, and thus confirm the shift toward a more conscious and developed know-how. A diagnostic campaign was addressed to define the minero-petrographic and chemical features of the investigated materials, taking into account compositional analogies and differences among the samples under analysis.





**Figure 2.** Ground floor plan of the *Theatrum Marcelli*, showing the *Ambulacro dei Cavalieri* and the *Piccolo ambulacro superiore*, along with the corresponding masonry techniques and building materials used in the monument construction, modified from Rossetto and Buonfiglio, 2010 [20].

### 3. Materials and Methods

A total of 10 samples of different artificial stone materials were collected from diverse areas of the *Theatrum Marcelli*. Sampling was conducted with criteria such as maximum representativeness and minimal invasiveness, using the most appropriate stainless-steel tools (e.g., lancets and small chisels). A comprehensive list of the samples, including material types and descriptions of the sampling points, is provided in Table 1.

**Table 1.** List of the analysed samples and descriptions of the sampling locations and types of materials.

Sample ID	Sampling Location	Description
TM_1	<i>Ambulacro dei Cavalieri</i> (fornice 4)	Mortar ( <i>opus testaceum</i> )
TM_2	<i>Ambulacro dei Cavalieri</i> (fornice 4)	Yellow brick
TM_3	<i>Ambulacro dei Cavalieri</i> (fornice 4)	Mortar ( <i>opus reticulatum</i> )
TM_4	<i>Ambulacro dei Cavalieri</i> (fornice 4)	Mortar
TM_5	<i>Ambulacro dei Cavalieri</i> (fornice 4)	Three-layer plaster
TM_6	Fornice 10	Mortar ( <i>opus reticulatum</i> ), external coating
TM_7	Fornice 10	Mortar ( <i>opus reticulatum</i> ), internal wall
TM_8	Fornice 12	Mortar ( <i>opus reticulatum</i> ), central wall
TM_9	Fornice 15	Mortar ( <i>opus reticulatum</i> ), central wall, Augustan age
TM_10	Fornice 15	Mortar ( <i>opus reticulatum</i> ), central wall, Julio-Claudian age

The samples were then embedded in epoxy resin and, once polymerized, cut and polished to obtain thin sections for petrographic observation under a Polarized Optical Microscope (POM). Microchemical analysis was carried out by means of a Scanning Electron Microscope (SEM) used in backscattered electron (BSE) mode and coupled with an Energy-Dispersive Spectrometer (EDS).

POM investigations aimed to gather information on the textural and mineralogical features of the samples.

An examination of the aplastic inclusions and the aggregate fraction (i.e., monomineralic crystals and polymineralic lithic fragments in both cases) was conducted for the brick and mortar/plaster samples, respectively. In this regard, the granulometry, morphology, distribution, and packing of the inclusions were evaluated. In addition, the microstructure and the optical activity of the groundmass and the binder were described [27]. The binder/aggregate ratio and macroporosity (% area) were established in the mortar and plaster samples using standard comparison charts on images acquired by optical light microscopy [28]. Particular attention was given to the documentation of fractures, as well as primary and secondary macroporosity due to secondary alteration and degradation processes. The estimation of petrographic observations was conducted using a ZEISS Primotech TL/RL microscope equipped with an AxioCam ERc 5s Rev.2 camera to capture images.

The scanning electron microscope (SEM) analyses were conducted on carbon-coated cross-sections using an Ultra-High-Resolution SEM (UHR-SEM) ZEISS Cross Beam, following the instrumental conditions detailed below for image acquisition and EDS analysis, respectively: HV: 15 keV; probe current: 100 pA; working distance: 11 mm; image: BSE—SE-BSE signal; detector image: solid-state detector (SSD); Everhart–Thornley Detector (SE); and for EDS acquisition: HV: 15 keV; probe current: 100 pA; working distance: 12 mm; take-off angle: 40°; live time: 30 s.

The micro-chemical investigations provided a semi-quantitative estimation of the major chemical elements of the monomineralic grains and rock fragments within the samples, thus corroborating the optical microscopy examination [29]. Furthermore, the binder and groundmass chemical composition was analysed.

In the case of mortar and plaster layers, investigations were carried out to obtain information on the nature of the lime used as a binder. In this regard, a point analysis was performed on the core of the lime lumps within the samples. Their presence could be useful in providing information on the raw materials since their chemical composition is similar to that of the limestone used for the calcination process [30,31].

In order to determine the pozzolanic reactions that occurred between the aggregate fraction and the binder, several spot analyses were performed within the binder matrix as well (3 spot analyses for each analysed sample). Considering the atomic density of the analysed material, the actual size of the electron beam interaction spot is approximately 100–200 nanometres. Subsequently, the hydraulicity index (HI) of both the binder matrix and the lime lumps was calculated according to the following equation [32,33]:

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

Higher HI values indicate a greater hydraulic character of the mixture, as this is associated with the presence of materials which display a high pozzolanic activity, leading to the formation of calcium (alumino)silicate hydrate (C-(A-)S-H).

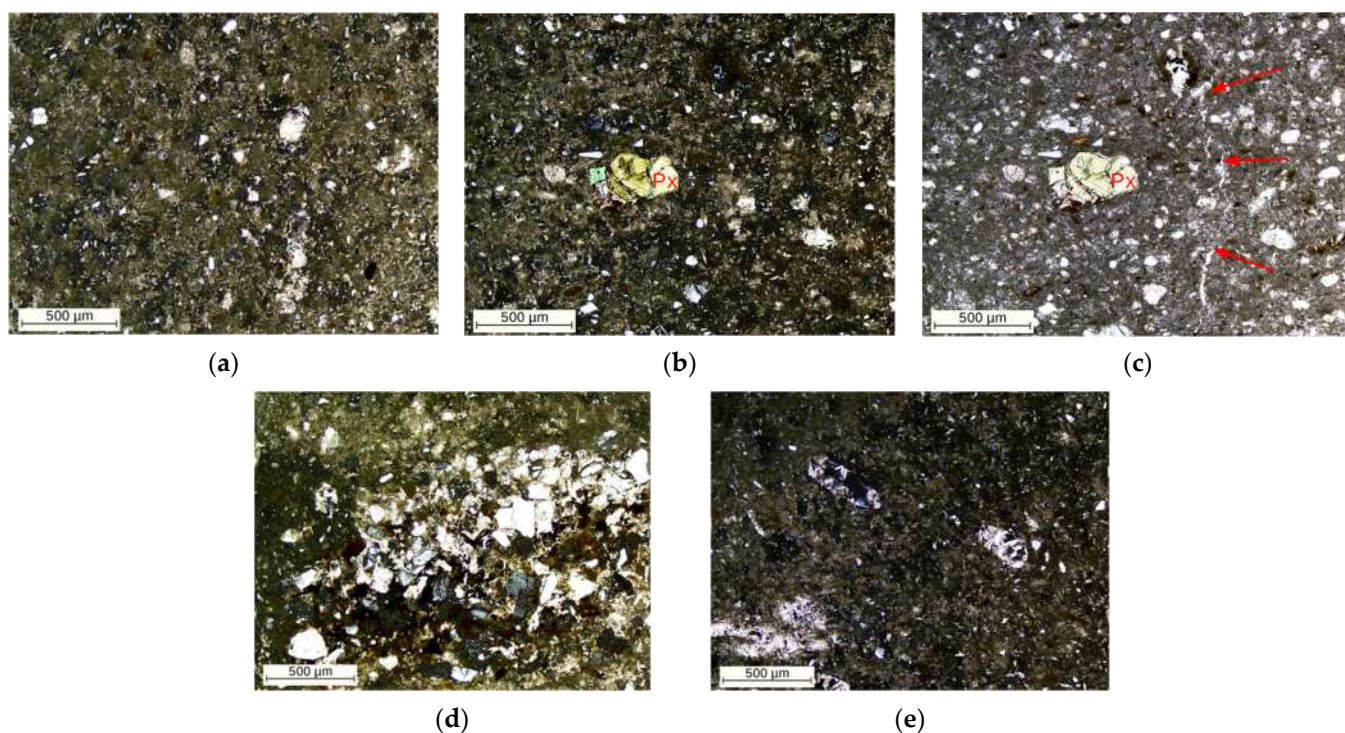
## 4. Results and Discussion

### 4.1. Bricks

The bricks used in the construction of the internal ambulatories of the theatre display a macroscopically homogeneous fabric and a light-yellow colour. They are approximately uniform in size and were carefully laid on a mortar bed, finished with a beaded jointing technique. The bricks are set within a cementitious core consisting of mortar and *caementa* made from crushed yellow brick, along with red and orange brick fragments arranged horizontally [20,26].

To investigate the compositional characteristics of the clay paste, a brick sample was collected from the innermost wall facing the *Ambulacro dei Cavalieri*.

Regarding the petrographic observations under POM, sample TM\_2 exhibits a fabric characterized by a relatively homogeneous spatial arrangement and a serial size distribution of aplastic inclusions (Figure 3a). The latter are mainly fine-grained, with larger grains only sporadically observed. Inclusion sizes range from coarse silt (0.03–0.06 mm) to very coarse sand (1–2 mm). The packing, estimated using comparative charts, is moderate, corresponding to approximately 20% [34]. Regarding the mineralogical composition of the aplastic grains, monocrystalline quartz is the dominant monomineralic phase, while pyroxene crystals are rare (Figure 3b,c). Calcareous lithic fragments are commonly recognized among the rock grains, while scoriae fragments are sporadic. Additionally, a large fragment of quartzarenite with carbonate cement was identified in the sample (Figure 3d). The groundmass is moderately homogeneous, showing low-to-absent optical activity and common clay lumps. These lumps generally suggest incomplete maturation and/or mixing of the raw clay [27].

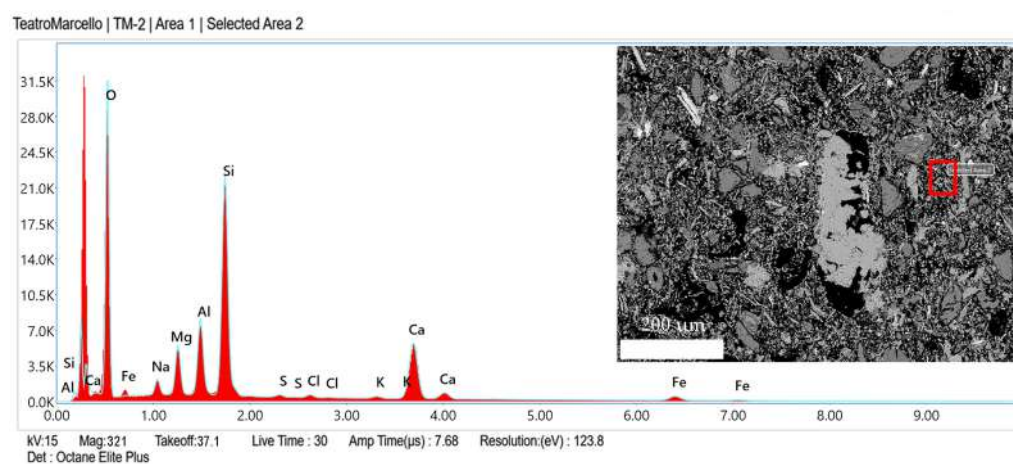


**Figure 3.** Representative micrographs of the TM\_2 brick sample showing (a) fabric characterized by a serial and homogeneous distribution of aplastic inclusions; (b,c) a pyroxene grain and a perpendicular shrinkage crack (red arrows); (d) large quartzarenite fragments with carbonate cement; (e) secondary calcite in the groundmass voids. Cross-polarised light acquisition was used for all the photomicrographs except for (c), captured with plane-polarised light. Legend: Px = pyroxene.



Porosity is low (<10%), with the predominant pore size class being <0.01 mm. Pores are partially filled with sparry calcite, precipitated within the pore network due to dissolution processes (Figure 3e). Perpendicular shrinkage cracks to the surface are also detected (Figure 3c).

SEM morphological observations, together with EDS chemical micro-analyses, confirmed the preliminary observations made through POM. Additionally, spot analyses (spot size 100–200 nm) were conducted on the groundmass, with the corresponding EDS spectrum shown in Figure 4. The results reveal a composition quite rich in SiO<sub>2</sub> (45.9%) and Al<sub>2</sub>O<sub>3</sub> (13.3%), along with smaller amounts of FeO (5.1%). Moreover, the high concentration of alkaline earth metals (MgO + CaO, 31.2%) can be attributed to the use of carbonate-rich clays. This might explain the light-yellowish coloration of the mixtures, although other factors linked to firing procedures and the kiln environment also contribute to the chromatic outcome and must be considered [35,36]. Further mineralogical analyses will be essential to fully understand and solve this aspect.



**Figure 4.** EDS micro-analysis on the clay groundmass of sample TM\_2 and corresponding SEM-BSE image showing the spot analysis area (red square).

## 4.2. Mortars and Plasters

### 4.2.1. Minero-Petrographic Analysis

Minero-petrographic observation was conducted under POM on different plaster and mortar samples collected from diverse areas of the theatre.

#### 1. Mortars

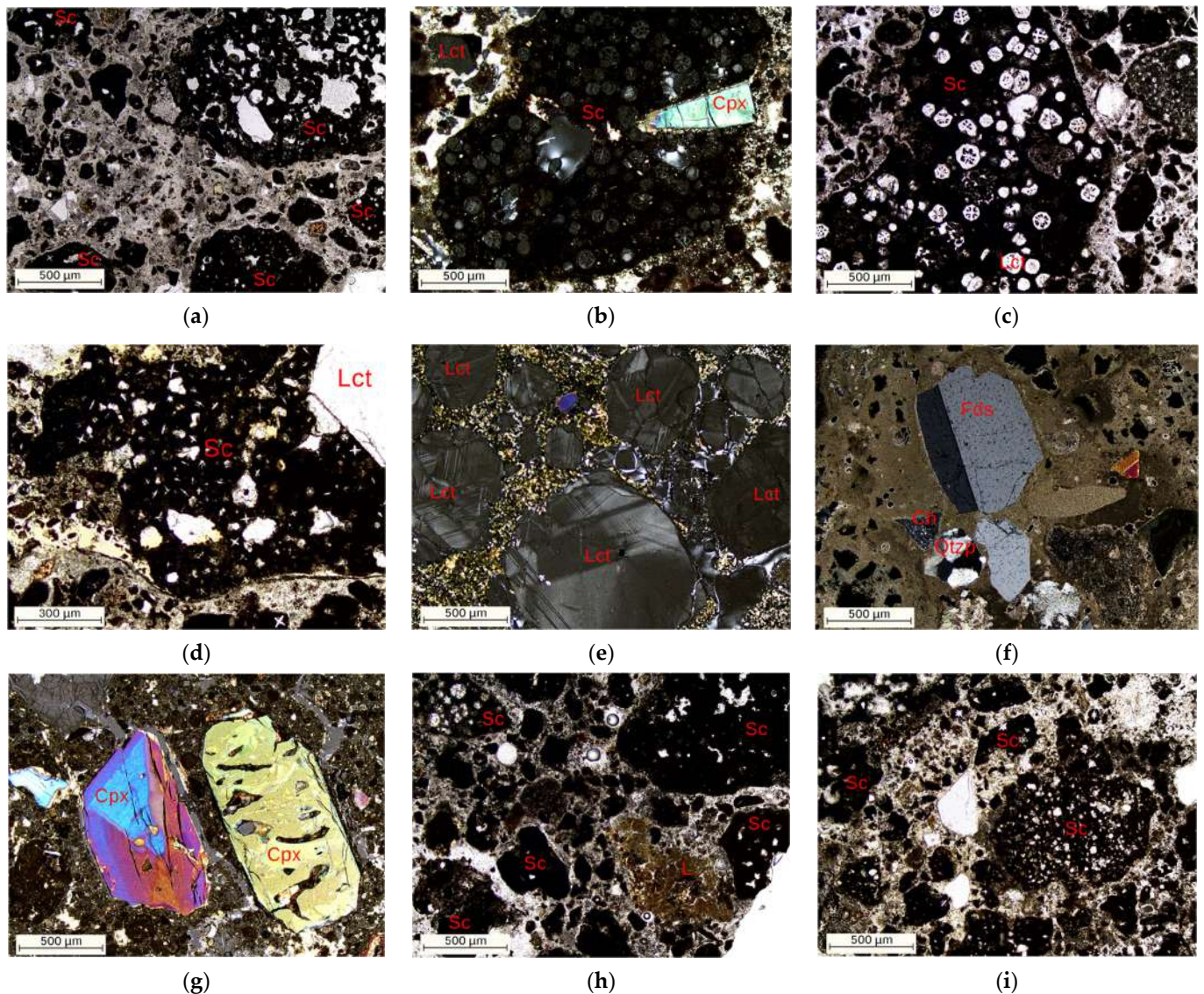
As for the mortars of the *Theatrum Marcelli*, the petrographic analyses revealed textural and compositional characteristics that were similar across the investigated mortar samples.

The *Theatrum Marcelli* mortars consist of an aggregate fraction that is generally poorly sorted and exhibits a bimodal distribution, occasionally shifting towards a serial distribution. The distribution of the aggregate within the binder matrix ranges from moderately homogeneous to heterogeneous. Concerning the shape of the aggregate, it varies from angular to subrounded across all the analysed samples [37]. The packing is relatively high, ranging between 60 and 70%, and only rarely dropping to 50%. Overall, the aggregate size spans from medium sand (0.25–0.5 mm) to coarse sand (0.5–1 mm) and very coarse sand (1–2 mm), with samples frequently including finer fractions (0.125–0.25 mm) [38].

All the samples exhibit a mineralogical and petrographic composition that seems compatible with the potassium-rich incoherent pyroclastic deposits of the Roman Magmatic Province (Figure 5). In more detail, the aggregate is characterized by pozzolanic volcanic components, predominantly comprising leucitic tephrite and leucitite fragments (as *scoriae*) (Figure 5a–d). The latter generally show porphyritic to oligophytic textures,



even though some highly porfirc individuals were observed. Within these *scoriae*, crystals of leucite (0.05–1.2 mm) (prevailing) and colourless–pale-green clinopyroxene (0.2–1 mm) are commonly recognized (Figure 5b). Leucite often displays a skeletal habit, resulting in a characteristic “star-like” morphology (Figure 5b–d,i). The groundmass appears reddish-brown with a variably vesiculated vitrophyric/criptocristalline texture. Occasionally, some fragments lack any phenocrystals. Additionally, individual crystals of clinopyroxene, leucite, and, more rarely, biotite have been observed within the aggregate fraction. In terms of granulometry, samples TM\_3 and TM\_9 also contain two grains of leucite and leucitic tephrite of larger dimensions characterized by a microcrystalline groundmass (Figure 5e).



**Figure 5.** Microphotographs acquired during POM showing (a) volcanic *scoriae* constituting the aggregate fraction in sample TM\_3; (b) a *scoria* in which both leucite and clinopyroxene crystals can be observed in sample TM\_1; (c,d) leucite crystals with a characteristic skeletal, star-like habit in samples TM\_7 and TM\_6, respectively; (e) a large grain of leucitic tephrite in sample TM\_3; (f) feldspar, polycrystalline quartz grains and a chert fragment in sample TM\_4; (g) clinopyroxene crystals in sample TM\_10; (h) a lump with internal shrinkage cracks in sample TM\_7; (i) clear reaction rims surrounding volcanic *scoriae* in sample TM\_1. Cross-polarized light acquisition was used for (b,e–g) photomicrographs, while (a,c,d,h,i) were captured with plane-polarized light. Legend: Sc = *Scoria*; Lct = leucite; Cpx = clinopyroxene; Fds = feldspar; Ch = chert; Qtzp = polycrystalline quartz; L = lump.

On the whole, the volcanic aggregate exhibits mineral–petrographic and textural characteristics that appear analogous to those of the pyroclastic deposits from the Colli Albani volcano. Indeed, the eruptive products of the Colli Albani district display a silica-undersaturated and ultrapotassic composition, ranging from tephrite to foidite (leucite) and tephriphonolite [11,12,39–42]. The dominant phenocryst phases mainly include leucite and clinopyroxene, some micas, and rare olivine, while the silica content is very low (<45 wt.%) [11,39]. The eruptive activity resulted in various successions of pyroclastic flows produced during different phases. The pozzolans used in Rome, mixed with lime to produce mortars with hydraulic properties, are actually the product of the final eruptive cycles of the Tuscolano–Artemisio phase (561–351 ka), characterized by a drier nature and associated with *Pozzolane Rosse* (460 ka), *Pozzolane Nere* (410 ka), and *Pozzolanelle* (355 ka) ignimbrites [41]. These deposits exhibit distinct petrographic and textural differences that allow their identification and differentiation in thin sections [13,43].

The optical observations of the aggregate of the *Theatrum Marcelli* mortars, with their distinctive, generally scarce porfirc index and the presence of colourless–pale-green clinopyroxene and leucite crystals (with prevailing skeletal star-like habits) within scoriae, suggest the use of the *Pozzolane Rosse* pyroclastic flow. In addition, the presence of *soriae* characterized by a higher porphyritic index is also found in the early explosive phase of the eruptive cycle [44].

The only noteworthy differences identified among the analysed samples regarding the aggregate fraction in terms of mineralogic phases include the presence of monocrystalline and polycrystalline quartz, feldspar, and trachytoid and chert lithic fragments in sample TM\_4, alongside the volcanic components described above (Figure 5f). Moreover, sample TM\_10 reveals a predominance of monomineralic phases, primarily consisting of clinopyroxene, feldspars, and biotite over *scoriae* (Figure 5g). In this case, the variability in the aggregate fraction components might be due to the different periods of execution of such mortars, which is attributable to a post-Augustan chronology (Julio-Claudian Age). Since feldspar is absent in the Alban Hills' volcanic products (it is rarely observed as a microcrystal in the groundmass of some lavas) [39], it is probable that it derives from the air fall and colluvial ash deposits from the Monti Sabatini volcanic district (San Paolo Formation, about 437 ka), which stratigraphically overlies the *Pozzolane Rosse* unit and in which sedimentary quartz is also recognized [12].

Moreover, the presence of crushed ceramic fragments (*cocciopesto*) within mortar sample TM\_1, taken from the *opus testaceum* wall inside the *Ambulacro dei Cavalieri*, could be seen as an attempt by the builders to produce an even more hydraulic and thus, durable, mixture. This is reasonable if we consider that these walls inside the *ambulacro* support the vaults of the *ima cavea* and are subject to quite humid conditions, promoted by the infiltration of meteoric water and facilitated by the numerous openings toward the seating tiers (*vomitoria* and basement windows) [26].

The binder matrix exhibits evident optical activity, with sub-rounded lime lumps of millimetric dimension frequently observed (Figure 5h). They show a peculiar porous and pelleted structure, which often shows clear internal shrinkage cracks [45,46]. Rare relicts of microfossils within the binder, likely residual and resulting from the rough calcination of the precursor limestone used to produce the lime, have also been observed. In all the analysed samples, clear reaction rims are evident at the interface between the binder and the aggregate, indicating the hydraulicization of the binder and the formation of hydrated phases (Figure 5i).

Porosity is very high, ranging from 20 to 30%, and comprises primary porosity, with predominantly subrounded pores, and secondary porosity, with irregular pores in the size



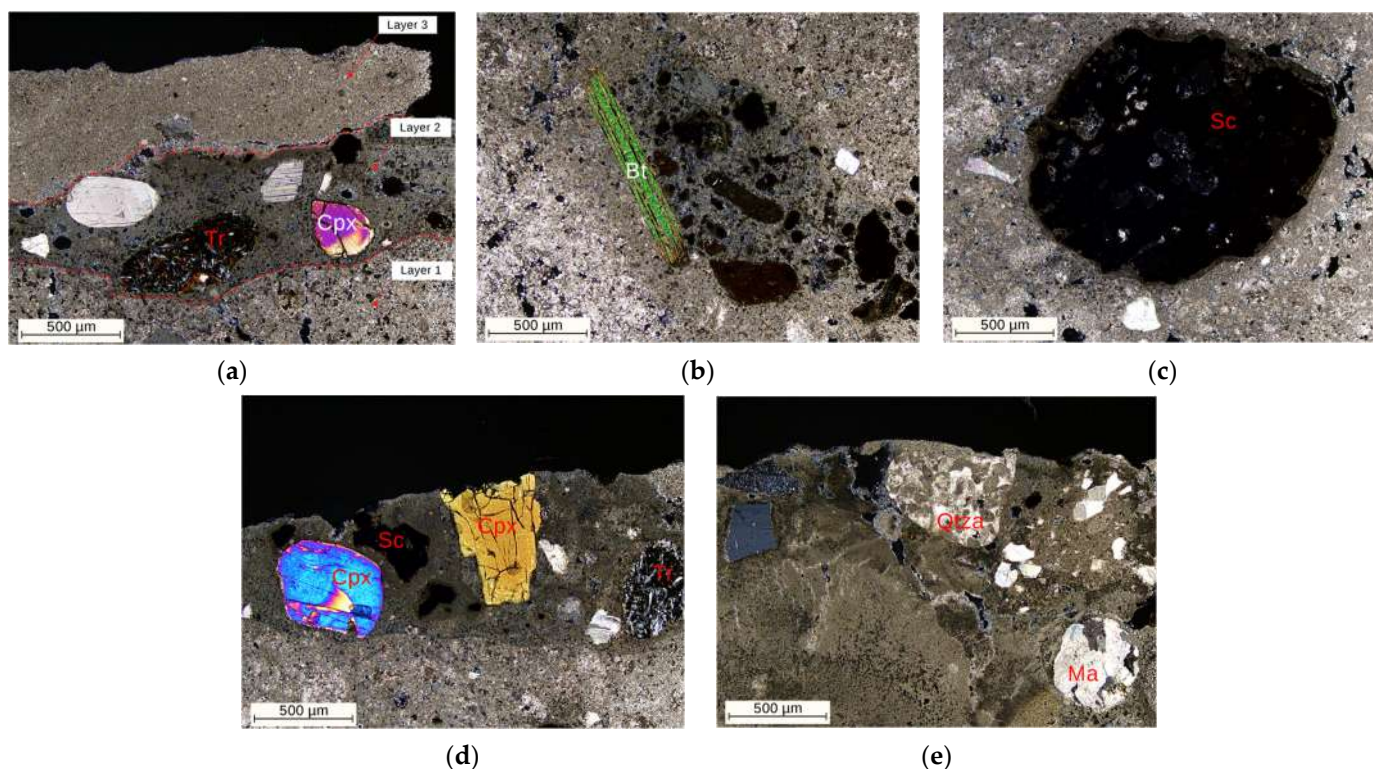
ranges of 0.1–1 mm and >1 mm. Furthermore, the recrystallization of calcite, due to the dissolution phenomena of the binder, is observed within the pores.

The aggregate-to-binder ratio, determined using comparative charts, is quite variable, averaging at approximately 3:1, in agreement with Vitruvian recommendations [14]. However, a 1:1 ratio of pozzolanic aggregate/binder is also frequently observed, suggesting the use of variable raw material proportions, as documented in other Roman constructions [1,47–49].

## 2. Plasters

As for the mortar samples, POM investigation was carried out on a plaster sample (TM\_5) collected from the *ambulacro dei Cavalieri (fornice 4)*. It revealed a stratigraphy composed of three distinct layers, differing in thickness and textural features.

The inner layer (Layer 1) (Figure 6a–c) is characterized by grains ranging from medium sand (0.25–0.5 mm) to coarse sand (1–2 mm). These grains exhibit a heterogeneous distribution and a bimodal sorting, with larger grains mixed with smaller ones. The packing is very low, at approximately 10%. In terms of the aggregate's composition, it includes sparse monomineralic crystals of monocrystalline quartz, pyroxene, and biotite, along with occasional *scoriae* grains. Lithic fragments of a carbonate nature, including marble and/or bioclasts (likely unburnt relicts of limestone after the process of calcination), are also identified. The binder, on the other hand, shows scarce optical activity with numerous lime lumps. Porosity is moderate, around 15%, and shrinkage cracks running parallel to the surface are also visible.



**Figure 6.** Representative micrographs of the TM\_5 plaster sample showing (a) the stratigraphy consisting of the three different layers, highlighted by the red dotted lines; (b) a biotite crystal and (c) a *scoria* grain within Layer 1; (d) clinopyroxene trachyte grains; and (e) quartzarenites and carbonate lithic fragments inside Layer 2. Cross-polarised light acquisition was used for all the photomicrographs. Legend: Tr = trachyte; Cpx = clinopyroxene; Bt = biotite; Sc = *Scoria*; Qtza = quartzarenite; Ma = marble.

The intermediate plaster layer (Layer 2) (Figure 6a,d,e) exhibits a variable thickness (860–460 microns) and a discontinuous development on the underlying layer. The aggregate is quite uniformly distributed and ranges from coarse sand (0.5–1 mm) to fine sand (0.125–0.25 mm), also displaying bimodal sorting. It is characterized by monomineralic grains of clinopyroxene and lithic fragments, including trachytes, *scoria*, quartz arenites with ferruginous cement, and carbonate lithic fragments derived from the comminution of limestone and marble. The binder appears cryptocrystalline and the porosity, as in the inner layer, is moderate.

The upper layer (Layer 3) (Figure 6a) is thinner (700–400 microns) and consists exclusively of the binder.

#### 4.2.2. SEM-EDS Investigation and HI Index

The semi-quantitative micro-chemical analyses were aimed at gaining a deeper understanding of the materials used as aggregates, obtaining information regarding the nature of the binder, and investigating the reactions between the binder and the aggregate.

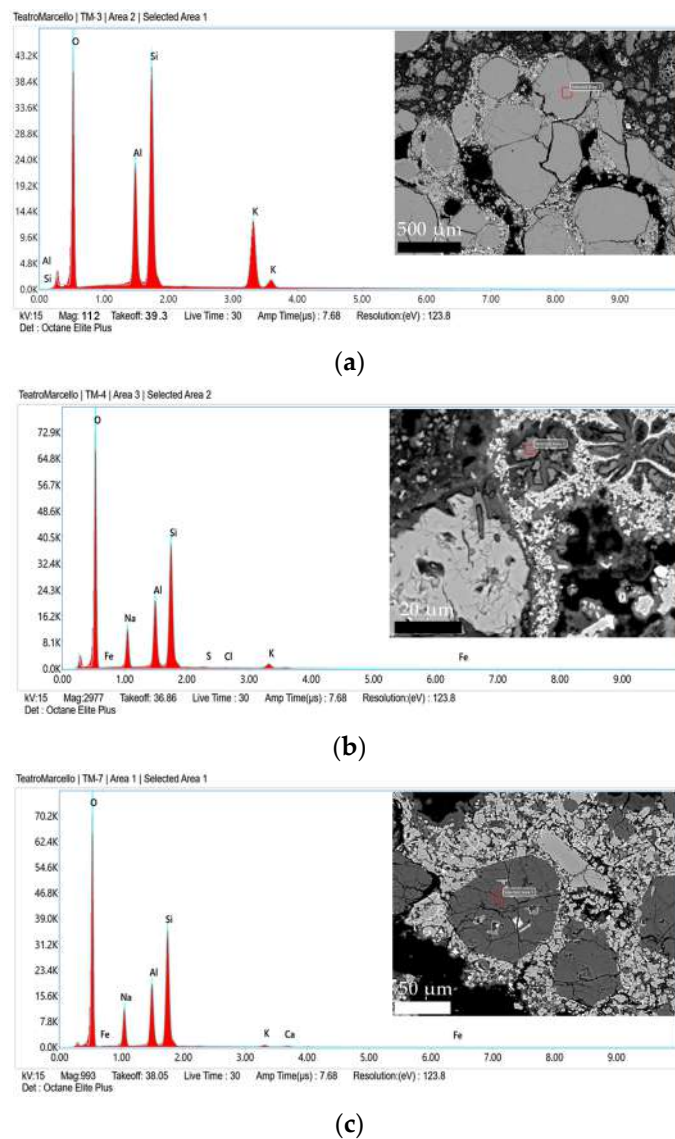
For the characterization of the volcanic aggregate, SEM-EDS point analyses were conducted on clinopyroxene crystals within the examined samples. The results reveal compositional values that, as in the case of clinopyroxenes from the *Pozzolane Rosse* ignimbrite, fall within the diopside field of the QUAD diagram, exhibiting terms particularly enriched in calcium. Nevertheless, the comparison using main oxides is not successful in terms of establishing the provenance of deposits, because all clinopyroxenes of the Roman Volcanic Province fall more or less in the same compositional field (diopside–salite) [43,50].

Microchemical analyses were also carried out to investigate the composition of leucite crystals. The results from the SEM-EDS investigation reveal the presence of a zeolitic alteration process, with leucite crystals observed either as individual crystals or within the groundmass, often partially or completely replaced by analcime (Figure 7a–c). Analcime inclusions were also detected within the internal cavities of the grains (Figure 7b). Conversely, larger crystals appear generally fresh and unaltered (Figure 7a).

These features suggest the use of volcanic aggregate derived from intermediate alteration facies corresponding to the transitional Bt to Bw horizon of the *Pozzolane Rosse* marine isotope stage 11 paleosol, characterized by authigenic components formed through argillitic and zeolitic alteration [12]. These authigenic minerals, produced by specific weathering processes, exhibit a higher alkali content, which reacts with lime to form potassic-, sodic-, calcic-, alumina-, and ferric-calcium-silicate hydrates, surprisingly resulting in high-quality cements that remained durable even under extreme climatic conditions [12,15]. The mineralogical observations, together with the data obtained from the semi-quantitative EDS analyses, likely indicate the consistent use of volcanic ash comparable to *Pozzolane Rosse* eruptive products in the mortars and plasters of the *Theatrum Marcelli*. This finding is particularly significant, as it reveals that the *Theatrum Marcelli* construction represents a key expression of the evolution of Roman construction techniques and mortar production technology, which would later form the foundation of the construction program adopted by Augustus. Indeed, it was only from the 1st century BCE, during the transition from the late Republican to the early Augustan period, that builders systematically improved the mechanical properties of mortars by selectively incorporating *Pozzolane Rosse* in the aggregate fraction. The presence of this type of pyroclastic deposit as an aggregate is observed for the first time in the mortars of Temple B in the Sacred Area of Largo Argentina, constructed after the fire of 111 BCE [10]. Previously, crushed fragments of tuff and volcanoclastic sediments from the San Paolo and Aurelia formations at the foot of the Capitoline Hill were commonly used [10]. These materials likely correspond to the *harenae cana* (“greyish in colour”) described by Vitruvius, which, due to their earthy consistency



and low compactness, formed the basis for poorly durable mortars [2]. In contrast, Vitruvius recommended volcanic sand ranging in colour from red (*rubra*) to black (*nigra*), which “makes a harsh, raspy, grating noise when rubbed vigorously in the hand”, as the optimal choice. According to [2,12,13], this likely corresponds to the red and black pyroclastic deposits of the *Pozzolane Rosse*.



**Figure 7.** SEM-EDS investigations on leucite/analcime crystals detected within the aggregate of the plaster/mortar samples: (a) EDS spectrum of a fresh leucite crystal observed in sample TM\_3 and corresponding SEM-BSE image showing the spot analysis area (red square); (b) EDS spectrum of some analcime inclusions inside the cavities of a leucite grain in sample TM\_4 and corresponding SEM-BSE image showing the spot analysis area (red square); (c) EDS spectrum of a leucite crystal completely replaced by analcime in sample TM\_7 and corresponding SEM-BSE image showing the spot analysis area (red square).

SEM-EDS chemical analyses also allowed us to conduct compositional studies of the binder used in the production of mortars and plasters. Table 2 shows the results of the SEM-EDS micro-chemical analysis with the corresponding HI calculated for both the binder and the lumps.

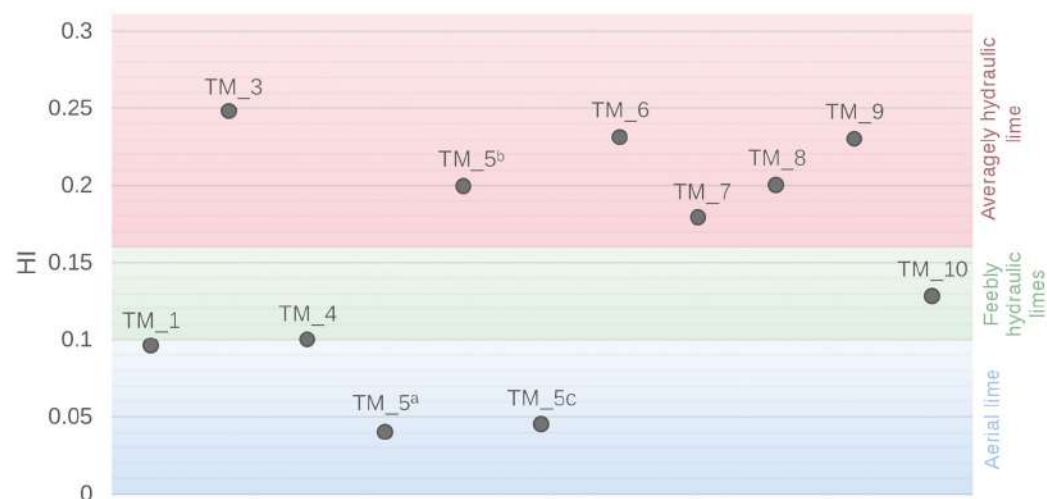
**Table 2.** Average values of the main oxides (wt.%) determined through SEM-EDS analysis on the binder (3 spot analyses for each sample) and on the lumps detected within the samples. TM\_5<sup>a</sup>: upper layer; TM\_5<sup>b</sup>: intermediate layer; TM\_5<sup>c</sup>: inner layer.

Sample ID	Type	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	S	Cl	K <sub>2</sub> O	CaO	FeO	HI
TM_1	Binder	0.6	7.8	1.8	6.8	0.5	0.0	0.5	81.9	0.0	0.096
TM_3	Binder	0.5	0.3	4.9	14.5	0.5	0.4	1.4	77.7	0.0	0.248
TM_4	Binder	0.5	6.3	2.0	6.9	0.4	0.0	0.8	83.0	0.0	0.100
TM_5 <sup>a</sup>	Binder	1.5	2.7	1.0	2.7	0.6	0.5	1.8	73.8	0.0	0.040
TM_5 <sup>b</sup>	Binder	1.8	4.6	3.5	12.1	1.5	1.0	1.8	73.8	0.0	0.199
TM_5 <sup>c</sup>	Binder	0.5	2.7	0.4	3.8	0.6	0.5	0.1	91.5	0.0	0.045
TM_6	Binder	1.2	0.3	4.3	13.7	1.0	1.3	1.1	77.4	0.0	0.231
TM_7	Binder	0.6	2.3	5.0	9.6	0.7	0.2	2.1	79.4	0.0	0.179
TM_8	Binder	0.0	0.8	4.3	12.0	0.8	0.3	0.9	80.9	0.0	0.200
TM_9	Binder	0.0	0.6	4.7	13.7	0.6	0.4	0.7	79.3	0.0	0.230
TM_10	Binder	0.2	0.3	2.8	8.2	1.9	0.4	0.5	85.7	0.0	0.128
Sample ID	Type	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	S	Cl	K <sub>2</sub> O	CaO	FeO	HI
TM_1	Lump	0.0	0.0	0.0	0.4	0.0	0.0	0.4	98.2	0.0	0.004
TM_1	Lump	0.0	0.4	0.3	1.3	0.0	0.0	0.0	97.3	0.0	0.016
TM_4	Lump	0.3	0.9	1.3	3.8	0.8	0.0	0.9	91.8	0.0	0.055
TM_4	Lump	0.2	1.2	1.6	4.1	0.8	0.0	0.9	91.4	0.1	0.063
TM_7	Lump	0.2	0.0	0.0	0.2	0.0	0.3	0.0	99.2	0.0	0.002
TM_8	Lump	0.0	1.1	0.0	1.2	0.0	0.0	0.0	97.7	0.0	0.012

Point analyses (spot size 100–200 nm) of major elements carried out on lime lumps within the samples provided significant insights into the nature of the binder. The formation of these lumps is a topic widely debated in the literature. Their origin is believed to result either from the slaking of quicklime, caused by the use of the minimum amount of water sufficient to convert CaO into Ca(OH)<sub>2</sub> [51,52], or from inadequate and poor mixing of the aggregate and lime [53]. Other hypotheses link their formation to the maturation phase, during which a carbonate crust develops on the surface of the lime putty [54]. In any case, once they are formed, the lumps gradually convert into calcium carbonate due to the carbonation process. As a result, these binder-related particles are fundamental for characterizing the raw materials used in mortar production, as their composition reflects that of their precursor limestone.

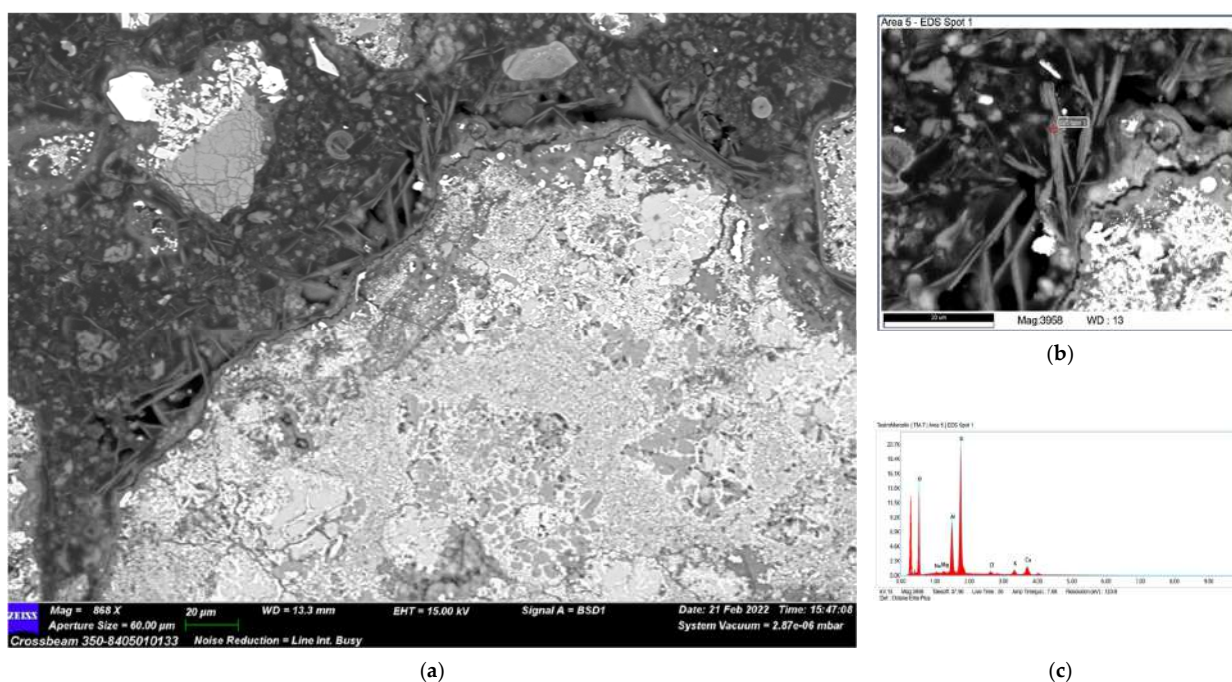
To minimize contamination from the aggregate, analyses were conducted on the innermost areas of the lumps. The results revealed a predominantly carbonate composition, with high CaO + MgO contents ranging from 92.6 wt.% to 99.2 wt.% and minor concentrations of SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub>. The hydraulicity index (HI) calculated for the lime lumps displayed very low values, between 0.002 and 0.063, indicating the aerial nature of the lime used in the production of all the analysed mixtures (HI < 0.10).

Similarly, point analyses were performed on homogeneous portions within the binder matrix to determine the hydraulicity index achieved through the addition of pozzolanic aggregate. EDS analyses revealed higher concentrations of SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub> and lower CaO + MgO contents compared to those measured in the lime lumps. The hydraulicity index calculated for the binder fraction showed values ranging from 0.038 to 0.248. Specifically, samples TM\_1, TM\_4, and TM\_10 fall within the range of feebly hydraulic limes (0.10 < HI < 0.16), while samples TM\_3, TM\_5 (intermediate plaster layer), TM\_6, TM\_7, TM\_8, and TM\_9 may be considered as averagely hydraulic limes (0.16 < HI < 0.31). Finally, in the upper and lower layers of sample TM\_5, the values are comparable to those of aerial limes (HI < 0.10) (Figure 8).



**Figure 8.** Graph showing the hydraulicity index (HI) values of the binder calculated for each sample and corresponding hydraulicity ranges. TM\_5<sup>a</sup>: upper layer; TM\_5<sup>b</sup>: intermediate layer; TM\_5<sup>c</sup>: inner layer [32].

The results are in line with the traditional Roman preparation techniques of mortar/plaster pastes. The latter were indeed produced through the calcination of highly pure carbonate rock, thus resulting in a binder of a predominantly aerial nature. In this regard, it is well known that Roman builders primarily selected calcareous raw materials, mainly limestones quarried from Monte Soratte and the Monti Cornicolani, which on average exhibit a CaO content of 90% [13,55]. Thus, the lime in question lacked hydraulic properties, which were instead imparted to the mixture through the addition of volcanic aggregate [56–58]. This aggregate reacted with the hydrated lime to form cementitious hydration products. These compounds are clearly observable in the analysed samples, as they exhibit characteristic needle-like morphologies under SEM-BSE and a composition rich in silica, alumina, and alkali (Figure 9).



**Figure 9.** (a,b) SEM-BSE acquisitions of C-A-S-H phases at the interface between the *scoriae* and the binder in sample TM\_7 showing peculiar needle-like morphologies and (c) corresponding EDS spectrum.

## 5. Conclusions

This diagnostic campaign conducted through complementary analytical techniques has provided valuable insights into the artificial stone materials (bricks, plasters, and mortars) used in the construction of the *Theatrum Marcelli*. The data obtained from petrographic and semi quantitative micro-chemical investigations not only allowed for the characterization of the raw materials, but also offered a deeper understanding of the production technology and the technological level achieved by early Imperial builders.

The bricks used in the internal ambulatories of the *Theatrum Marcelli* exhibit a homogeneous light-yellow fabric with fine-grained inclusions, predominantly quartz, and calcareous lithic fragments. The presence of a moderate concentration of alkaline earth metals (MgO + CaO) might suggest the use of carbonate-rich clays.

On the other hand, plasters and mortars were produced using raw materials with a relatively uniform composition. This confirms the typical “recipe” employed in the Roman era for making natural hydraulic mortars through adding pozzolanic material to lime. The pozzolanic component is mainly represented by leucitic tephrites and leucitites (as *scoriae*), as well as monomineralic grains of clinopyroxene, leucite, and rare biotite. This volcanic aggregate is consistent with ultrapotassic products from the Roman Magmatic Province, likely linked to the eruptive cycle of the Colli Albani volcanic district and comparable to the *Pozzolane Rosse* ignimbrites. The only compositional difference in the aggregate fraction among the analysed samples is the additional presence of monocrystalline and polycrystalline quartz, feldspar, trachytoid, and chert lithic fragments in sample TM\_4, which may correspond to the air fall and colluvial ash deposits from the Monti Sabatini volcanic district that overlies the *Pozzolane Rosse*.

The presence of *Pozzolane Rosse* within the mortars/plasters of the *Theatrum Marcelli* highlights a key advancement in Roman construction techniques.

This practice, emerging during the transition from the late Republican to the early Augustan period, emphasizes the systematic improvement in mortar mechanical properties through the selective incorporation of *Pozzolane Rosse*. These findings position the *Theatrum Marcelli* as a significant case study in the evolution of Roman architectural technology, reflecting innovations that would later characterize the building program of Augustus.

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