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Mortar recipes from the Roman Imperial Bath-Gymnasium and Urban Mansion of Sagalassos – A technological perspective

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ABSTRACT

This work presents the results of the examination of mortars from the archaeological site of Sagalassos in Anatolia (Ağlasun, Burdur Province, Southwest Turkey). The 36 specimens were selected from structures within the Roman Imperial Bath-Gymnasium and Urban Mansion, respectively dating to the 1st-6/7th century CE and the 1st century BCE-7th century CE. These samples underwent macroscopic, microscopic, physical, granulometric and spectroscopic examinations to identify the raw materials and how these were processed. Most importantly, at least five different mortar recipe types were revealed. This diversity emphasises that mortar production was flexible and empirical, probably following a general but not strict procedure. Overall, this research contributes to a better understanding of construction technology at Sagalassos during the Roman Imperial Period and Late Antiquity, a time when mortar materials were systematically used on a large scale.

1. Introduction

Mortars have been defined as materials obtained by combining binder, aggregate, water, and additives or admixtures (EN 16572, 2015). From the 10th millennium BC, mud was the first binder used in the Near East and it was then followed by pyro-technological products such as gypsum and lime binders (Artioli et al., 2019). Before the 2nd century BCE, mortars made of mud, lime or gypsum were mainly used for non-structural purposes in the form of plastering (Artioli et al., 2019). Around the 2nd century BCE, the Romans made an important contribution as they employed mortars for masonry and structural purposes to a large scale (Adam, 2005). Roman mortars have been regarded of being made from secret ingredients and particular recipes (Adam, 2005). Overall, the archaeological evidence points out to the consistent use of lime alongside natural pozzolans and/or artificial pozzolans and/or other local raw material resources (Artioli et al., 2019). Despite this, it remains unclear whether the process of mortar making was a standardized or unstandardized procedure at specific sites.

Previous studies have prevalently investigated mortars from Italy and the western Roman provinces with the primary aims of mineralogical and chemical characterization (Cuevas et al., 2023). To a lesser extent, studies focused on the eastern Roman provinces with the aims of understanding technological and provenance aspects (Uğurlu Sağın et al., 2021). Most recently, the field saw the development of recognizing recipe types at certain sites which could further shed light on mortar production (Boese et al., 2023; Fort et al., 2023). This work revolves around the mortars of the archaeological site of Sagalassos to enhance our understanding on Roman and Late Antique mortar technology as at this time mortar materials were systematically used with lime-based mortars starting to be applied. The primary goals are: (i) clarifying the composition of the mortars, (ii) identifying mortar recipe types and (iii) addressing standardization and possible diachronic implications. For this purpose, macroscopic examination, thin-section petrography, bulk density and open porosity, dry sieving and Fourier-transform infrared spectroscopy have been applied.

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2. Archaeological setting

2.1. The site and case study of Sagalassos

The archaeological site of Sagalassos (37°40′41″N, 30°31′10″E) is situated in modern day Southwestern Turkey, 109 km north of Antalya and 7 km north of the modern town of Ağlasun in the Burdur Province (Fig. 1; Poblome et al., 2019).

In the late 20th century, the ancient city of Sagalassos and its territory started to be thoroughly investigated (Poblome et al., 2019). Nowadays, more than three decades of excavation and interdisciplinary research by the KU Leuven, starting from the end of the 1980 s until the present day, have provided numerous insights into the history and development of the archaeological site (Poblome et al., 2019). Among these, archaeometric studies of a wide range of ancient materials have highlighted aspects of provenance and technology (Degryse and Waelkens, 2008).

2.2. The Roman Imperial Bath-Gymnasium

The Roman Imperial Bath-Gymnasium has been under excavation since 1995. This building complex, covering more than 5000 m^2 in surface area, is situated on a natural hill at the transition from the upper to the lower city (Fig. 2). The earliest known public baths of Sagalassos were built in the mid-1st century CE. During the late 1st- early 2nd century CE, these so-called Old Baths were incorporated into a new complex: the Bath-Gymnasium (Beaujean et al., 2023). Many changes and renovations to its internal organization and layout were carried out until the 4th-5th century CE. After the archaeological excavations, it was possible to recognize elements of the "Roman bathing suites" such as *caldaria*, *frigidaria*, *tepidaria* and *apodyteria* (Beaujean et al., 2023). The Roman Imperial Bath-Gymnasium played a key role in society as the building was used to accommodate the city's inhabitants as well as local festival visitors with bathing. The Roman Imperial Bath-Gymnasium remained in use until the late 6thcentury CE (Beaujean et al., 2023).

2.3. The Urban Mansion

The Urban Mansion has been under excavation since 1995. This building complex is situated in the eastern residential quarter of the city (Fig. 3). The initial occupation of the site of the Urban Mansion goes back to the second half of the 1st century BCE and included the construction of at least two Roman Imperial peristyle dwellings (Uytterhoeven, 2023). It was not until the late 4th- early 5th century CE that the complex reached its largest expansion (Uytterhoeven et al., 2013). Archaeological excavations highlighted that this area was an upper-class residence, in fact thus far about 90 spaces on different terraced levels have been exposed (Fig. 3; Uytterhoeven et al., 2013). The occupation of this area came to an end around the mid-7th century CE (Uytterhoeven et al., 2013).



Fig. 1. Map showing the Eastern Mediterranean Basin (bottom-left) and the southwestern part of Anatolia with the location of Sagalassos (main map).

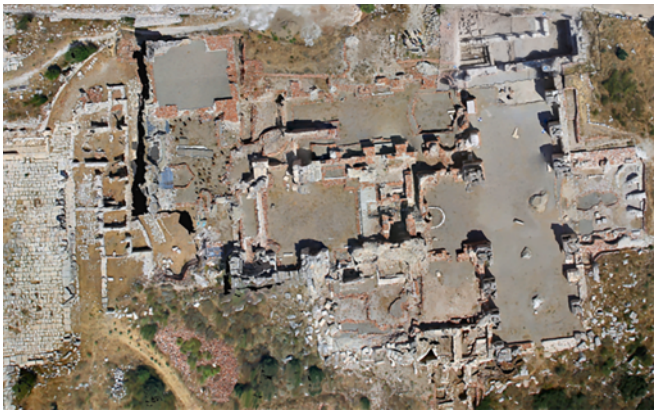


Fig. 2. Aerial view of the excavated parts of the Roman Imperial Bath-Gymnasium at Sagalassos as of 2014 (after Ergenç et al., 2022: 111368, Fig. 2).



Fig. 3. Aerial view of the Urban Mansion at Sagalassos in 2023 (Courtesy of Sagalassos Archaeological Research Project).

2.4. Construction materials with special reference to mortar research at Sagalassos

At Sagalassos, construction materials mainly consist of natural stone, brick and tile, and mortar. These have been under investigation since the start of the project.

Natural stone encompasses limestone, conglomerate, breccia, travertine, marble, volcanic tuff, granite, sandstone and siltstone (Degryse et al., 2003). Macroscopic, petrographic and chemical analyses showed that most of the building stone had a local origin (Degryse et al., 2003; Muchez et al., 2008). Marbles are an exception as these were imported (Degryse et al., 2003).

The brick and tile that were used are classified as coarse wares of Fabric Group 3 (Degeest, 2000). These ceramics were analysed petrographically, mineralogically and chemically indicating that the clay raw materials originated from the site itself or from nearby areas such as Köyönü, Yazır and Ağlasun (Degryse and Poblome, 2008; Joris, 1998).

Research on mortars has been mainly carried out between the end of the 1990s and the start of the 2000s (Callebaut et al., 2000; Degryse et al., 2002; Viaene et al., 1997). These studies have advanced our understanding by providing several insights into: (1) the nature and composition of the mortars, (2) the provenance of the volcanic raw materials used and (3) the most suitable materials for conservation

practice. The first pilot study by Viaene et al. (1997) provided an overview of the composition of mortars used in Sagalassos. Essentially, this research showed that lime was used as a binder and that limestone, volcanics – pumice and lava fragments – and crushed ceramics were the main aggregates added (Viaene et al., 1997). Further research focused on an in-depth examination of the volcanic aggregates (Callebaut, 1995; Callebaut et al., 2000). Mineralogical, petrographic and geochemical analyses of geological and archaeological samples showed the provenance of the volcanic raw materials, corroborating that these came from the nearby Gölçük region, about 5 km north of the site (Callebaut, 1995; Callebaut et al., 2000). The study of the mortars at Sagalassos was continued by Degryse et al. (2002) to find a suitable repair mortar for conservation and restoration. For this purpose, several experimental mortars were designed based on previous petrographic and mineralogical observations and experimental mixtures using local raw materials readily available in the region of Isparta (Degryse et al., 2002). These were tested for strength and frost resistance to replicate Sagalassos-specific conditions (Degryse et al., 2002). It was pointed out that the most appropriate mortar to survive the climatic environment at Sagalassos consisted of a mixture of lime and crushed volcanics (Degryse et al., 2002). Even though mortars containing ceramics provided great waterproofing, they were too weak in case of frost (Degryse et al., 2002).

3. Materials and methods

3.1. Materials

Mortar material was made available for investigation at the Geology Division of KU Leuven after sampling was carried out in the excavation seasons from 1993 to 2010. A total of 36 samples were selected from various architectural structures of the Roman Imperial Bath-Gymnasium and the Urban Mansion (Supplementary Material 1). The assemblage encompassed mortars used for a number of purposes — e.g. bedding, flooring, plastering and pointing (Supplementary Material 1). These were located in moisture-rich and non-moisture settings (Supplementary Material 1). The samples are dated between the 1st century BCE and the 5th/6th century CE according to the building phases identified during the archaeological excavations (Beaujean et al., 2023; Uytterhoeven et al., 2013). Particularly, the sample selection from the Roman Imperial Bath-Gymnasium principally focused on the late 1st- early 2nd century CE, while the ones from the Urban Mansion mainly focused on the late 4th- early 5th century CE.

3.2. Methods

3.2.1. Macroscopic visual inspection

Prior to manipulation, all 36 samples were subjected to macroscopic visual inspection (Supplementary Material 2). A range of diverse characteristics were recorded including topography, hardness, roughness, texture, pores and fissures, presence of layers and their adhesion, binder colours, main components and surface treatments. These features were chosen to be noted as they could provide information on the nature of the sampled mortars. Furthermore, this examination on macroscopic appearance helped to make initial groupings of the assemblage for a better understanding of mortar recipe types.

3.2.2. Thin-section petrography

Thin section slides with a thickness of 30 μm were made of all 36 samples (Supplementary Material 2). The samples were impregnated with a low viscosity epoxy resin developed by TAAB that is coloured with a fluorescent yellow dye. This was used because of the friable and porous nature of the samples as well as to ensure a better visualization of the pores. Considering the layers present in some of the samples, petrographic analysis was carried out on 44 thin sections (Supplementary Material 2). The slides were examined using a Leica DM750P polarising microscope with magnifications ranging from 50x to 200x using cross polarised light (XPL) and plane polarised light (PPL). Photos of the thin sections were taken with a Sony A7 II camera equipped with polarizers. The system for recording the frequencies of the different components followed the terminology and abundance charts based on Stoops (2021). Petrographical analysis was performed as it is usually the most effective method to highlight information such as binder type and structure, main aggregates and porosity. This information is then used to better understand details of the texture and composition of the mortars. These characteristics can refine the initial groupings of the assemblage and identify specific mortar recipe types. Mortar recipe types were identified when the binder textural features, the same kind of aggregates and their frequencies were comparable. Possible sub-types within the same recipe were identified when there was a distinct variation in the frequencies.

3.2.3. Bulk density and open porosity by water immersion

Measurements on bulk density and open porosity accessible to water at ambient temperature were carried out on the whole assemblage ($n = 36$) of mortars (Supplementary Material 2). The procedure followed recommendations on 'Porosity by immersion' outlined by Thomson et al. (2004). At first, representative mortar specimens weighing at least 5 g were dried at low temperatures for 24 h in an oven at 50°C until constant weight. The dried samples were then weighed using a Laboratory Sartorius Universal scale to find the mass of the oven-dried mortar (M_{dry}). Subsequently, the sample was kept in distilled water for 24 h in a beaker. After removing the excess water off with chamois leather, the sample was weighed with the previously mentioned scale to find the mass in air of the water-saturated mortar (M_{sat}). Finally, the mass in water or apparent mass (M_{hyd}) was found by a hydric scale setup on the aforementioned scale. The data was processed using R Studio software Version 4.2.2 (RStudio Team, 2022). This information is used to understand whether these properties are reflected in the function and/or recipe types.

3.2.4. Dry sieving after manual separation

A sub-set of mortar fragments ($n = 28$) weighing at least 10 g were carefully crushed in agate mortar and pestle for 10–15 min in circular motion after Casadio et al., 2005 (Supplementary Material 2). This is important to remove the adhering binder from the aggregates as much as possible making sure not to break the aggregates. After crushing, the sample was weighed using a Mettler Toledo AX224 analytical balance. The crushed material was passed through seven Retsch test sieves ranging from 63 μm up to 4.75 mm while a Retsch mechanical vibratory sieve shaker AS200 was operated for 10 min at 1.20 amplitude. The retained material caught by each sieve was weighed on the same scale. In this procedure, some samples were discarded for different reasons (such as not enough material or very complex stratigraphy). Where possible, the thickest layer was crushed for layered samples. The data was processed using R Studio software Version 4.2.2 (RStudio Team, 2022) and Microsoft Excel Version 2308. This method was selected as it can give insights into the proportions of the binder to aggregates as well as the range of aggregate particle sizes.

3.2.5. Fourier-transform infrared spectroscopy (FTIR)

FTIR was performed to examine the binder-rich fraction obtained after mechanical separation from sieve analysis. As a result, the fraction < 63 μm of 28 specimens was tested (Supplementary Material 2). The preparation of the sample followed the KBr pellet method. A few micrograms of powdered sample and about 50 mg of KBr were mixed using a micro-spatula in an agate mortar. This mixture was then transferred into a pellet and pressed at 1.8 tonnes for 30 s in a Specac hydraulic handheld press. The collection of spectroscopic data was provided by using a Thermo Scientific Nicolet iS5 spectrometer with iD1 Transmission instrument. The collected spectra ranged between 4000 cm^{-1} and 400 cm^{-1} at 4 cm^{-1} resolution. The number of scans was set at 98 as this setting improved the ratio of signal to noise. Additionally, this

longer and more in-depth scanning was deemed appropriate for the identification of organic matter. The identification and interpretation of the spectra was supported by the use of OMNIC 9 software in combination with an infrared spectra library of archaeological materials created by the Kimmel Center for Archaeological Science Infrared Standards Library, Weizmann Institute of Science (Kimmel Center for Archaeological Science, 2023). By screening for inorganic and organic compounds in the binder-rich fraction, this method was chosen in order to identify the binder, the finest aggregate fractions and organic substances. Based on the binder characteristics, this examination allowed to clarify the main trends across recipe types.

4. Results

4.1. Macroscopic visual inspection

Generally, the samples present a range of different colours going from shades of brown, pink, white and grey. The mortars are relatively compact with mostly uneven surfaces. The samples are mainly harsh or rough in feel and hackly or irregular in texture. Pores and fissures are evident, mainly having round, irregular or elongated shapes. Layers are occasionally seen, and they have good adhesion. Typically, mortars used for bedding purposes do not present any layers, while layers are evident in mortars used for other purposes. Overall, the material is not very hard, but rather hard or soft. It appears that greyish mortars are predominantly harder, while pinkish, whitish and brownish ones are softer. At first sight, the mortars have various inclusions with a diverse grain size reaching up to a couple of centimeters. These appear to be mainly minerals, rock fragments, ceramic and lime particles. A handful of samples present surface treatments. These consist of white impressions on flooring mortars and paint on wall plasters from the Urban Mansion.

4.2. Thin-section petrography

Initially, mortar samples were macroscopically grouped according to the colour of the binder and aggregates. The petrographic observations

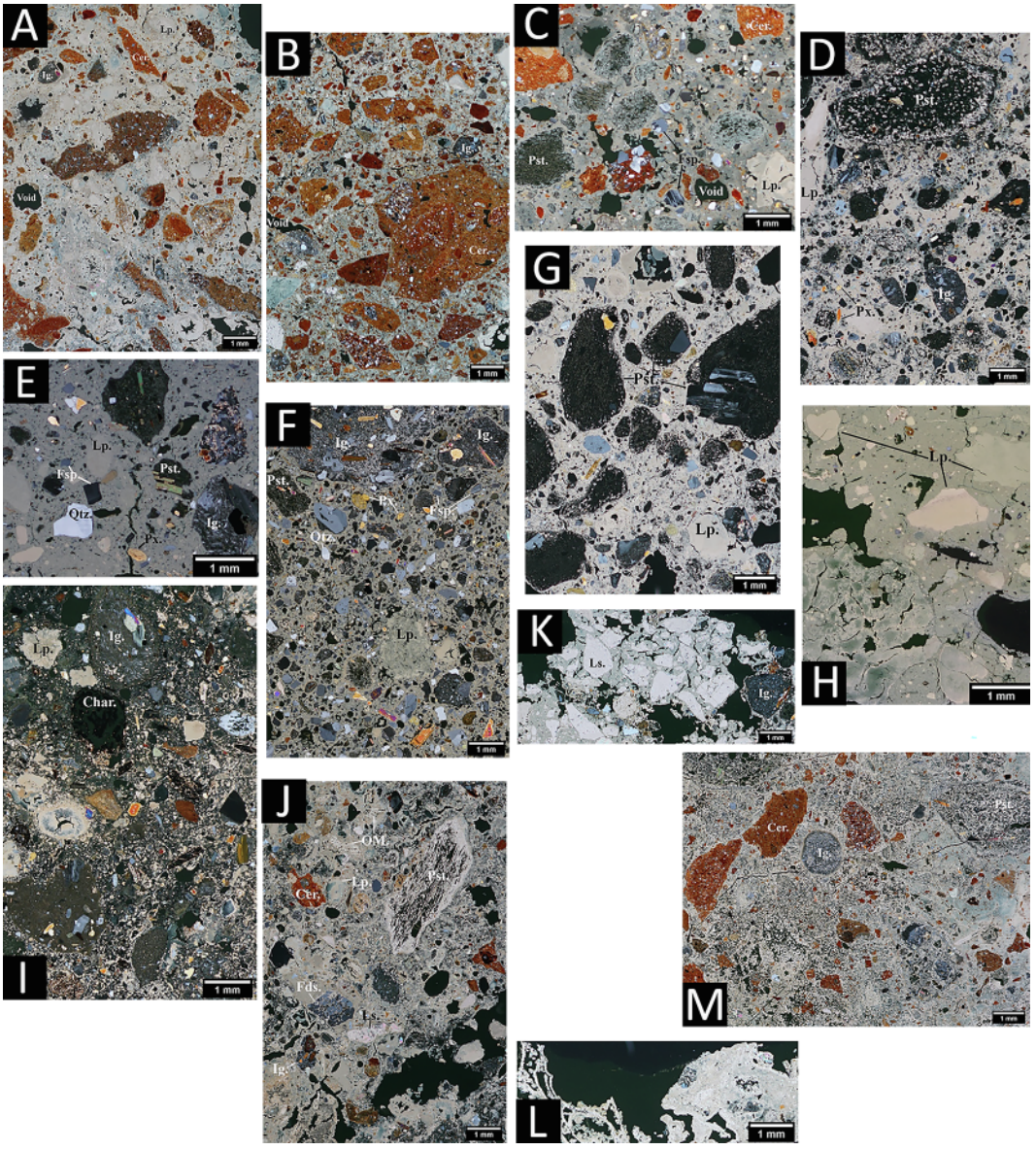


Fig. 4. Thin-section microphotographs of selected sample fabrics in cross-polarised light (XPL) with 1 mm scale Cer. = Ceramic, Char. = Charcoal, Ig. = Igneous, Lp. = Lump, Ls. = Limestone, OM. = Organic material, Pst. = Pumice, Fsp. = Feldspar, Px. = Pyroxene, Qtz. = Quartz and Void. (a) Sample 1.2, Fabric 1A; (b) Sample 47, Fabric 1B; (c) Sample 5, Fabric 2; (d) Sample 7, Fabric 3A; (e) Sample 35.1, Fabric 3B; (f) Sample 43, Fabric 3C; (g) Sample 40, Fabric 4; (h) Sample 33.2, Fabric 5; (i) Sample 3, unique; (j) Sample 11, unique; (k) Sample 50.1, unique; (l) Sample 42.1, unique; (m) Sample 62, unique.

made it possible to refine the initial macroscopic groups. As a result, different types of mortars were identified according to textural and compositional features. These could be further divided into sub-types in certain instances. Overall, this methodological approach has been proven valuable as it highlights the spectrum of mortars across a given site without applying the two-way classification of mortars with ceramics (*opus signinum/cocciopesto*) versus mortars without ceramics.

- *Ceramic-rich type 1 (Sample 1.1, 1.2, 2, 4, 14, 37, 42.2, 47, 48.2, 49, 50.2, 50.3)* is marked by the presence of coarse ceramic fragments. This type can be subdivided into two sub-types. Type 1A (Sample 1.1, 1.2, 2, 4, 37, 50.2) has a heterogenous micritic texture with few lime lumps (Fig. 4a). Furthermore, it presents dominant ceramics, usually elongated and angular to sub-angular in shape (Fig. 4a). Type 1B (Sample 14, 42.2, 47, 48.2, 49, 50.3) has a heterogenous micritic texture with very few to few lime lumps (Fig. 4b). It presents very dominant ceramics, mainly equated to elongated and sub-angular to sub-rounded in shape (Fig. 4b).
- *Ceramic and pumice-rich type 2 (Sample 5, 6, 8, 65)* can be distinguished by a homogenous micritic texture with few lime lumps. This type has frequent to dominant pumice, mainly elongated and rounded in shape (Fig. 4c). Also, it shows few to common coarse ceramic fragments, elongated and sub-angular (Fig. 4c). Finally, there are very few to few feldspars. Sample 8 presents the same materials, but it differs in texture and frequencies of the components. Specifically, it has a heterogenous micritic texture with few lime lumps. Additionally, it has frequent to dominant coarse ceramics, elongated and very angular to angular in shape, and few pumice, equated and elongated and sub-rounded in shape.
- *Volcanic-rich type 3 (Sample 7, 9, 10, 13, 33.1, 34.1, 35.1, 36, 41, 43, 45, 48.1, 61, 64)* is identified by the presence of volcanics and minerals – mainly feldspars and pyroxenes. The volcanic material includes pumice and igneous rocks with a trachytic texture with a basaltic and/or andesitic composition. This group is quite diverse, and it can be subdivided into three sub-types based on variations in the abundance of the components. Type 3A (Sample 7, 9, 10, 13, 48.1, 61, 64) has a heterogenous micritic texture with common to frequent pumice and few to common igneous rocks (Fig. 4d). Feldspars are few, while pyroxenes are very few to few (Fig. 4d). Type 3B (Sample 33.1, 34.1, 35.1) has a homogenous micritic texture with few lime lumps. Furthermore, it presents few to common feldspars, igneous rocks and pumice (Fig. 4e). Pyroxenes are few (Fig. 4e). Type 3C (Sample 36, 43, 45) has a homogenous micritic texture, showing common to frequent feldspars (Fig. 4f). Few to common igneous rocks as well as pumice are evident (Fig. 4f). These are equated and elongated and rounded in shape. Finally, other minerals such as pyroxenes, mica and quartz are very few to few (Fig. 4f). Sample 41 presents the same materials, but it differs in texture and frequencies of the components. Particularly, it presents a homogenous micritic texture with common igneous rocks, elongated and subrounded in shape, as well as few pumice, pyroxenes and feldspars.
- *Pumice-rich type 4 (Sample 12, 38, 39, 40, 46, 60)* usually presents a heterogenous micritic texture. It is characterized by frequent to dominant pumice material, elongated and sub-rounded to rounded in shape, often filled in with binder material (Fig. 4g).
- *Lump-rich type 5 (Sample 33.2, 34.2, 35.2)* is characterized by a homogenous micritic texture with dominant lime lumps, mainly elongated with a rounded and well-rounded shape (Fig. 4h).

Sample 3, Sample 11, Sample 42.1, Sample 50.1 and Sample 62 present key significant differences in terms of texture and composition compared to the rest of the assemblage. They are considered unique samples.

- *Sample 3* has a heterogenous micritic texture with few to common lime lumps. It shows frequent to dominant elongated and sub-rounded igneous rocks (Fig. 4i). There is also the presence of few charcoal or burnt plant material (Fig. 4i).
- *Sample 11* has a heterogenous micritic texture with few lime lumps. It exhibits few pumice (Fig. 4j). Additionally, a different range of materials such as igneous rocks, limestone, sedimentary rocks, coarse ceramics, organic material and feldspars appear to be very few to few (Fig. 4j).
- *Sample 50.1* has a homogenous micritic texture. It is characterized by very dominant limestone, elongated and sub-angular to sub-rounded in shape (Fig. 4k). Very few to few igneous rocks, equated and sub-rounded in shape, are present (Fig. 4k).
- *Sample 42.1* has a heterogenous micritic texture. It differs from the other samples because it has practically no aggregates (Fig. 4l). Nevertheless, feldspars are few while amphiboles, pyroxenes and igneous rocks are very few to few (Fig. 4l). This is most likely a precipitation layer of calcium carbonate.
- *Sample 62* is distinguished by a heterogenous sparitic or popcorn texture (Fig. 4m). In certain areas, it is possible to distinguish a bluish grey micritic texture. Additionally, there are few to common lime lumps. It presents common to frequent elongated angular to sub-angular coarse ceramics (Fig. 4m). Volcanic material can be distinguished, in particular pumice is few (Fig. 4m).

4.3. Bulk density and open porosity by water immersion

Density values are between 1.1–1.6 g/cm^3 with an average of 1.4 g/cm^3 (Fig. 5). The porosity of the samples ranges between 27.9–50 % with an average of 37.7 % (Fig. 5). Most of the sample fall within a range of 1.2–1.5 g/cm^3 and 35–40 % (Fig. 5). Evaluation of these basic physical properties according to different use shows that flooring mortars have slightly higher density compared to other functions with values consistently between around 1.5 g/cm^3 (Fig. 6). However, these mortars are not necessarily less porous (Fig. 6). Further evaluation on density and porosity showed the inverse relationship of the two. In terms of recipe groups, the least dense and most porous nature can be highlighted for *Pumice-rich type 4* and the most dense and least porous nature for *Volcanic-rich type 3C* (Fig. 7).

4.4. Dry sieving after manual separation

In order to provide satisfactory binder/aggregate estimates, the fractions passing a 125 μm mesh sieve were considered as the binder after Casadio et al. (2005). Overall, dry sieving by manual separation emphasized that binder/aggregate ratios are between 0.18–1.14 by weight with an average of about 0.44 by weight (Fig. 8). Most of the samples fall within 0.2–0.6 by weight (Fig. 8). In terms of percentages, almost all samples are composed of about 20–40 % binding material in the range of less than 125 μm in grain size (Fig. 9). The aggregate particles constitute about 80–60 % of the total mortar samples (Fig. 9). These have a wide range of different sizes. Aggregate particles coarser than 250 μm generally constitute above 40 % of the mortars, indicating that most of the aggregates have medium-sand size or above (Fig. 9).

4.5. Fourier-transform infrared spectroscopy (FTIR)

Spectroscopic analysis highlighted different aspects of the binder component of the mortars. Overall, the samples showed the typical peaks of a hydroxyl group around 3400 cm^{-1}, thus indicating structural and free water. All the samples presented clear peaks around 1430–1420 cm^{-1} (C-O stretching), 876 cm^{-1} and 712 cm^{-1} (C-O bending) (Figs. 10-12). These three peaks point to carbonates, specifically calcite. Generally, a typical peak around 1050 cm^{-1} with a recognizable asymmetric shape and coming from a shoulder near 1200 cm^{-1} (Si-O stretching) can be attributed to silicates (Figs. 10-12). Further peaks can be noted between the region of 800–400 cm^{-1}, also attributed to silica and silicates (Figs. 10-12). Apart from these

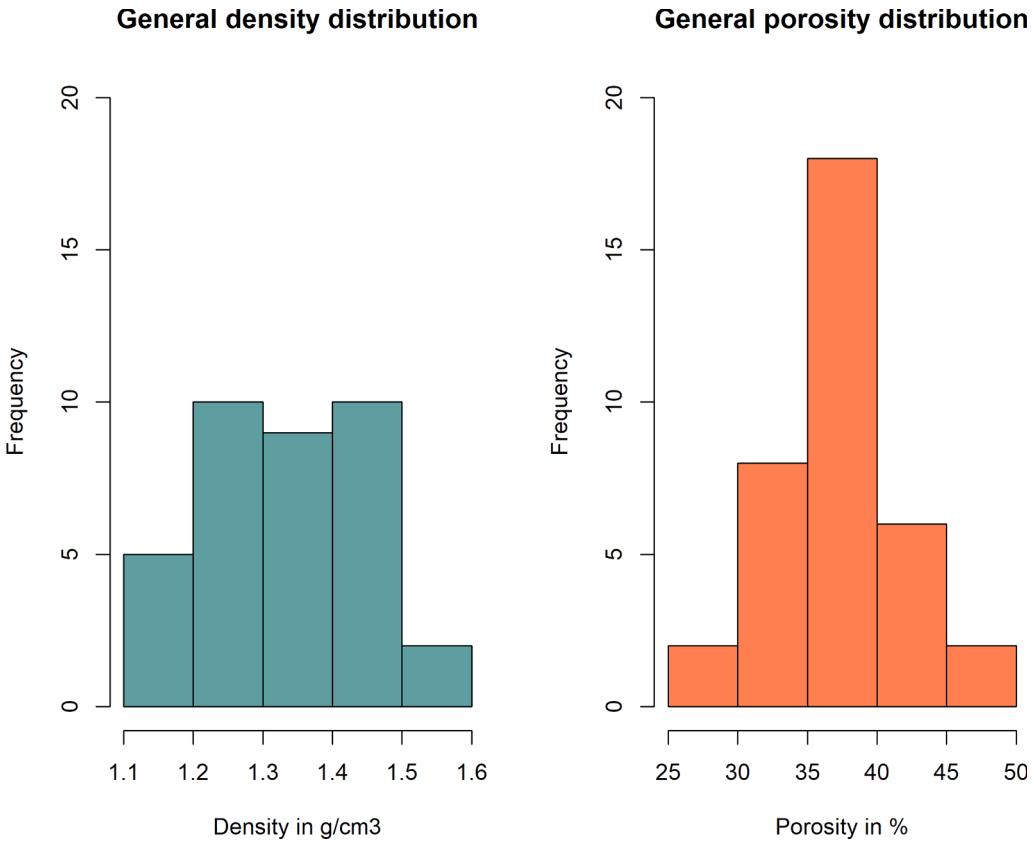


Fig. 5. Histogram showing the distribution of bulk density and open porosity after water immersion.

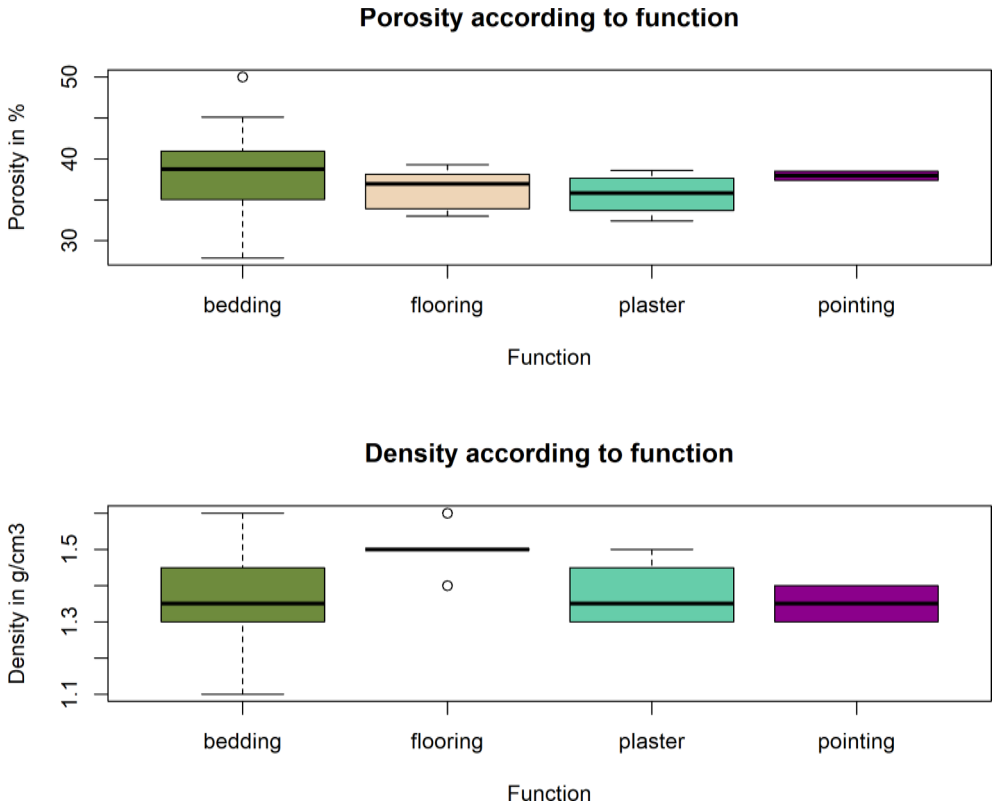


Fig. 6. Boxplot showing bulk density and open porosity according to function.

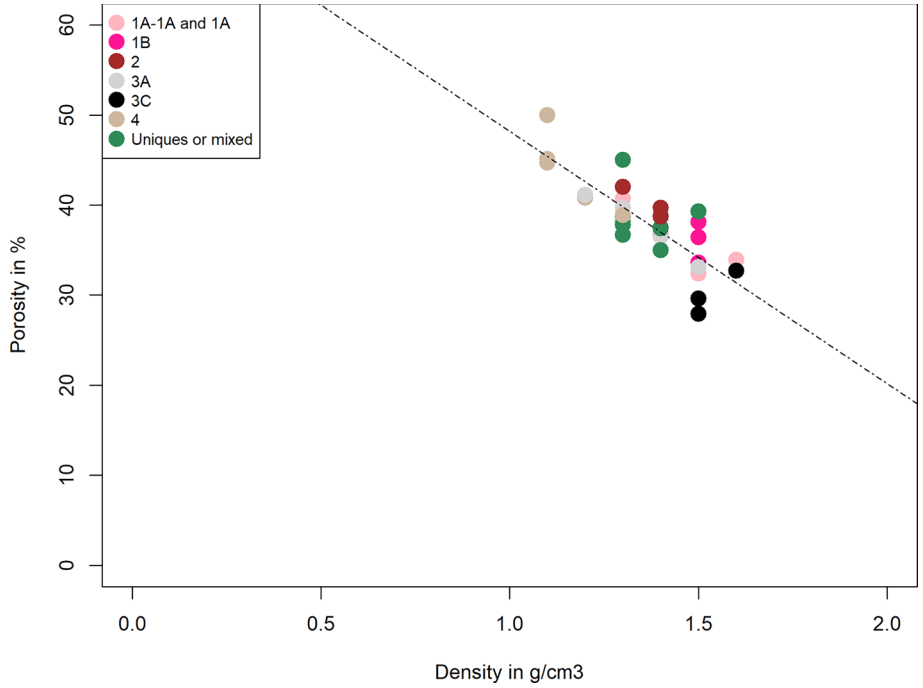


Fig. 7. Fitted line plot showing the inverse relationship between bulk density and open porosity according to petrographic groups.

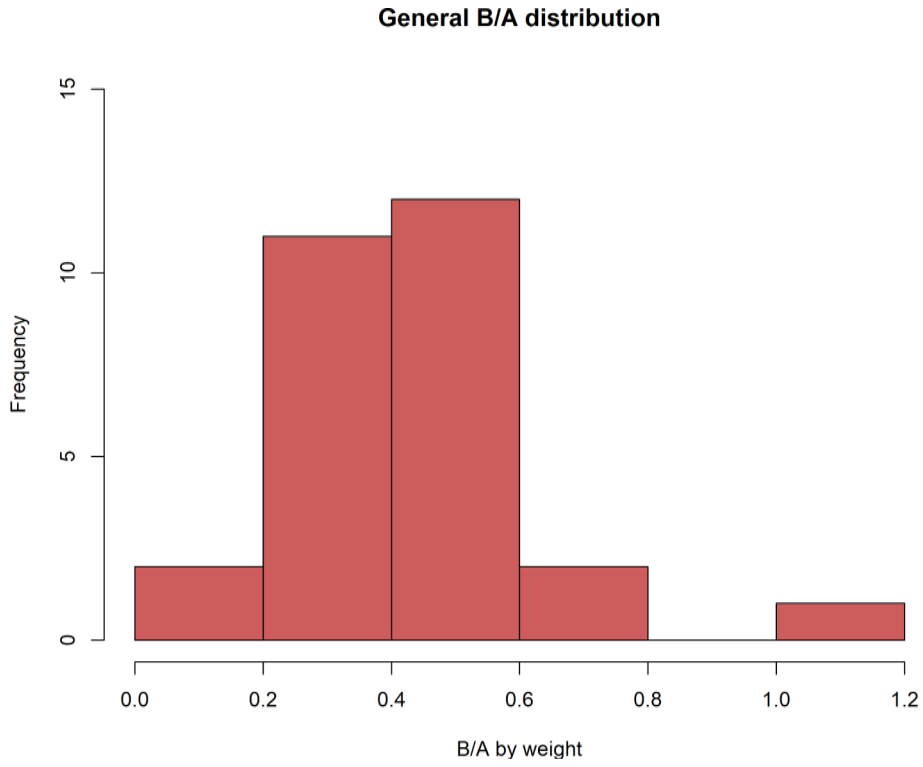


Fig. 8. Distribution of binder/aggregate ratio by weight.

observations, it should be noted that Sample 62 showed peaks around 1458 cm^{-1}, 1027 cm^{-1}, 878 cm^{-1}, 857 cm^{-1} and 712 cm^{-1} (Fig. 13). These point to calcite alongside aragonite, as well as silica and silicates. So far, peaks that could point to the addition of organics such as oils, waxes, glues or else were not detected in the binder-rich fraction of the mortars tested.

5. Discussion

5.1. Binder

Petrographic and FTIR analyses indicated that the mortars have a lime-based binder. Viaene et al. (1997) proposed that the source for this binder could be the pure limestones from the territory of Sagalassos. In Sample 62, the presence of aragonite observed by FTIR and its coarser

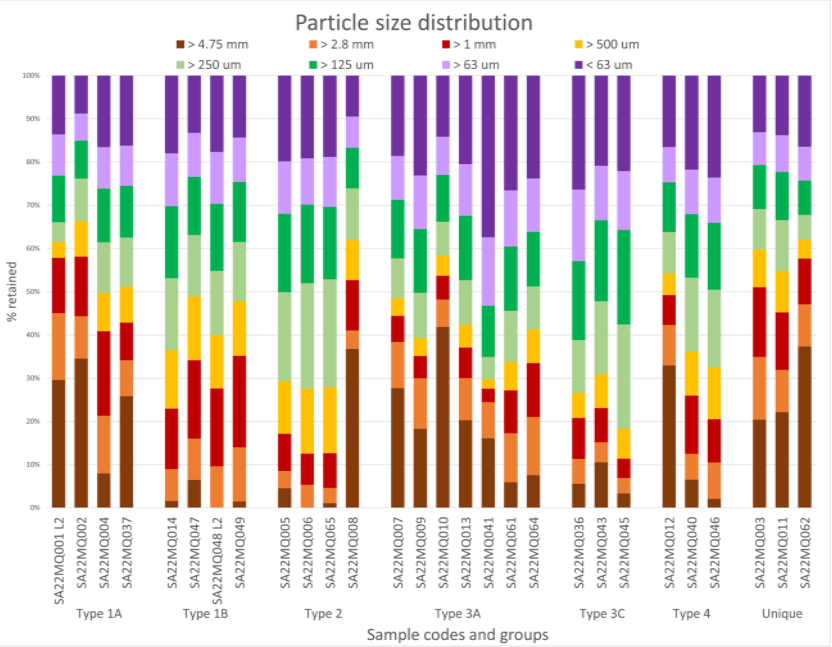


Fig. 9. Grain size distribution after dry sieving by manual separation according to recipe types.

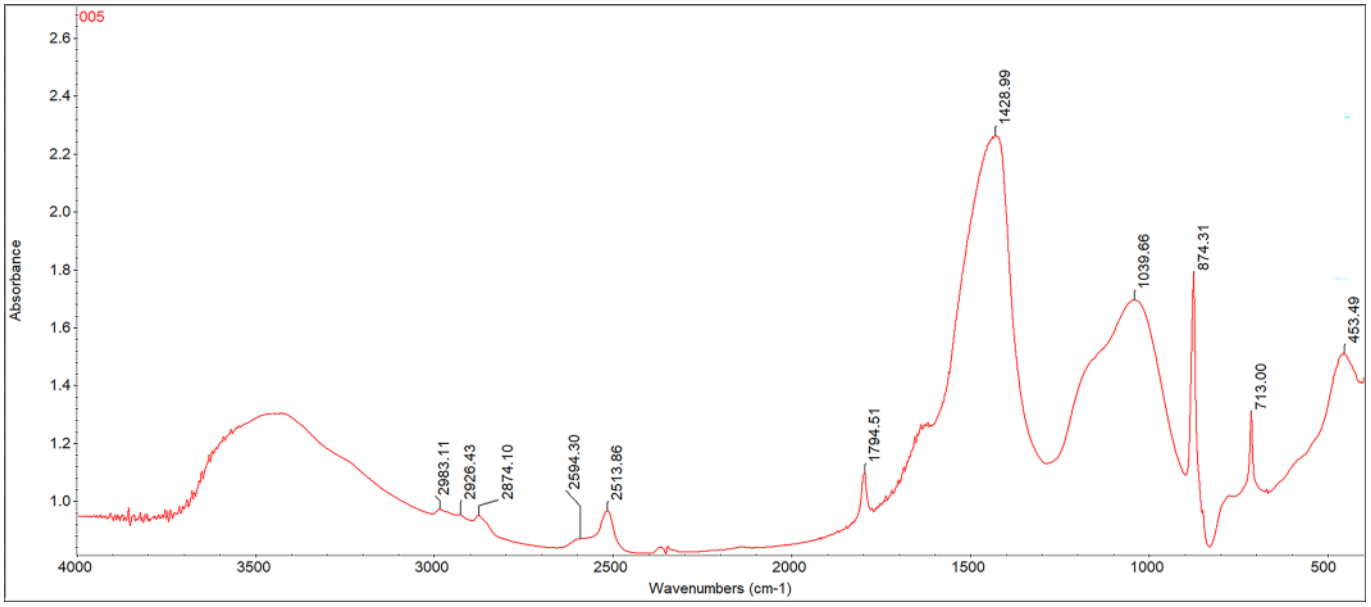


Fig. 10. FTIR spectrum of Sample 5, characteristic for recipe types 2 and 4.

'popcorn-like' texture under microscopy are peculiar. These features could have different explanations. Aragonite, an unstable polymorph of $CaCO_3$, could be biogenic as in mollusk shells, geogenic as in speleotherms and marine cements or pyrogenic as in mortars and wood ash (Singh et al., 2016; Toffolo, 2021). Pyrogenic aragonite seems the most likely explanation. Its presence in the binder fraction seems rather improbable to derive from bio-organisms or geological material given that bioclasts were not observed in thin section. In this case, aragonite could have most likely formed from the presence of magnesium and/or environmental factors across time (Diekamp et al., 2009; Frankeová and Koudelková, 2020; Singh et al., 2016; Toffolo, 2021). Mg-ions as well as moisture could favour and stabilize the formation of aragonite during hardening or dissolution and precipitation cycles (Diekamp et al., 2009; Frankeová and Koudelková, 2020; Singh et al., 2016; Toffolo, 2021). Mg-rich materials, such as dolomites or dolomitic limestones, are present in the area of Sagalassos which would make it a possible explanation (Muchez et al., 2008). In terms of environment, the sample was located in a moisture-rich environment such as the Roman Imperial Bath-Gymnasium. Additionally, many wet and dry cycles occur in the region where Sagalassos is located; in fact the site is subject to an Oro-Mediterranean climate with long, wet winters and short, dry summers (Paulissen et al., 1993). Finally, the formation of aragonite could be a product of the carbonation of hydrated phases, thus possibly indicating a natural hydraulic lime binder (Frankeová and Koudelková, 2020).

5.2. *Aggregates and additives*

Petrographic observations highlighted that coarse ceramic, pumice

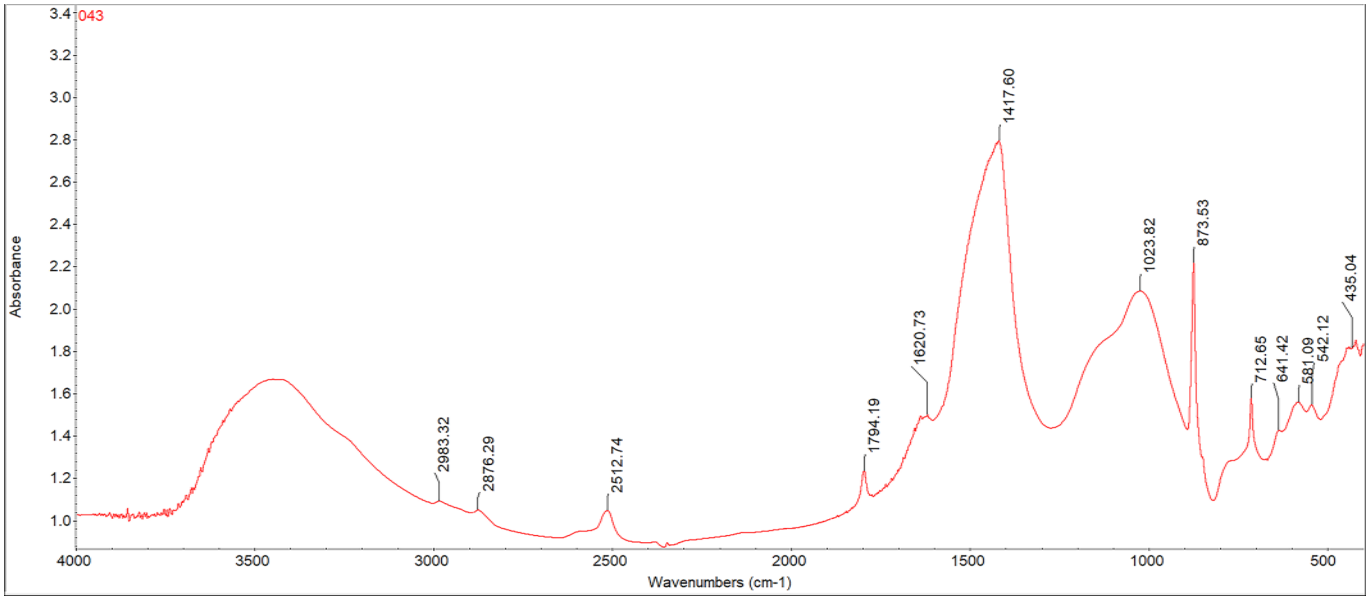


Fig. 11. FTIR spectrum of Sample 43, characteristic for recipe types 3A and 3C.

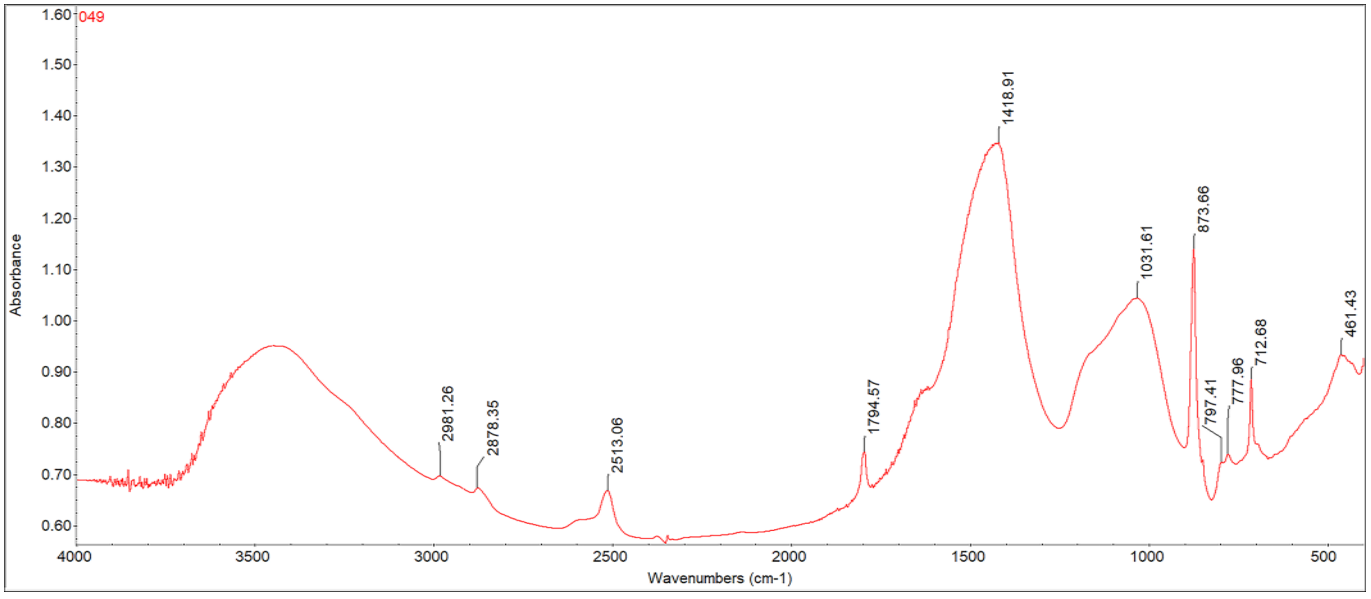


Fig. 12. FTIR spectrum of Sample 49, characteristic for recipe types 1A and 1B.

and fine-grained igneous rocks were the main intentional aggregate additions to the mortars. These materials emphasise that both artificial as well as natural pozzolana were used, probably to provide hydraulic properties. On a smaller scale, limestone was also intentionally added. It remains unclear whether the presence of other inclusions such as charcoal was deliberate or not. For example, charcoal could result from kiln contamination or it could have been added for darkening the colour of the mortar or absorbing moisture (Elsen, 2006; Ingham, 2011; Lancaster, 2021). At present, it can be assumed that all aggregates have local origin. Coarse ceramic could have been locally produced or recycled (Viaene et al., 1997). Volcanic materials, such as pumice and igneous rocks, were very likely obtained from the volcanic area situated northwest of the site (Muchez et al., 2008). Finally, Sagalassos is partially built on top of limestone and it is surrounded by it (Muchez et al., 2008).

As shown by FTIR examination, very fine siliceous materials were detected in the binder-rich fraction. These finest aggregates can also confer hydraulicity to the mortar material as they react with lime (Lancaster, 2019). The silicate bands were more evident in Type 1A, Type 1B, Type 3A and Type 3C. This may indicate a higher proportion of silicate phases and possibly increased hydraulicity. In the aforementioned cases, their nature can be determined by assessing spectral information with the library database as well as macroscopic and petrographic observations. It becomes clear that the pink mortars of Type 1B show a distinct FTIR spectrum with additional peaks around 800–750 cm^{-1}, likely pointing to the use of fine ceramic powders heated around 800℃ (Fig. 14). As a result, this could indicate that bricks, tiles and/or coarse wares were employed for the finest aggregates (Lancaster, 2019). Additionally, materials fired at these temperatures would have been able to react well with the lime for the making of a hydraulic mortar (Baronio and Binda, 1997; Lancaster, 2019). It is also possible to recognize that the greyish mortars of Type 3, specifically 3A and 3C, have characteristic spectra with additional peaks between 600–500 cm^{-1}, possibly suggesting the use of volcanic powders and ashes (Fig. 15). Finally, the absence of organic matter does not necessarily

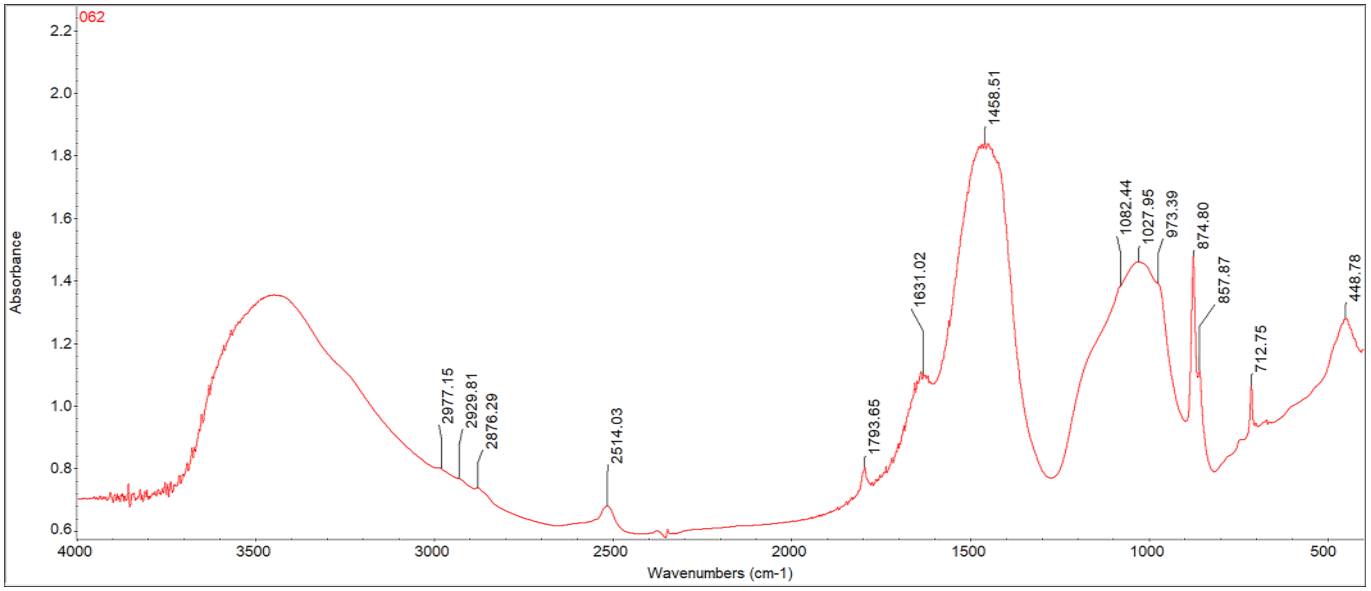


Fig. 13. FTIR spectrum of Sample 62, unique.

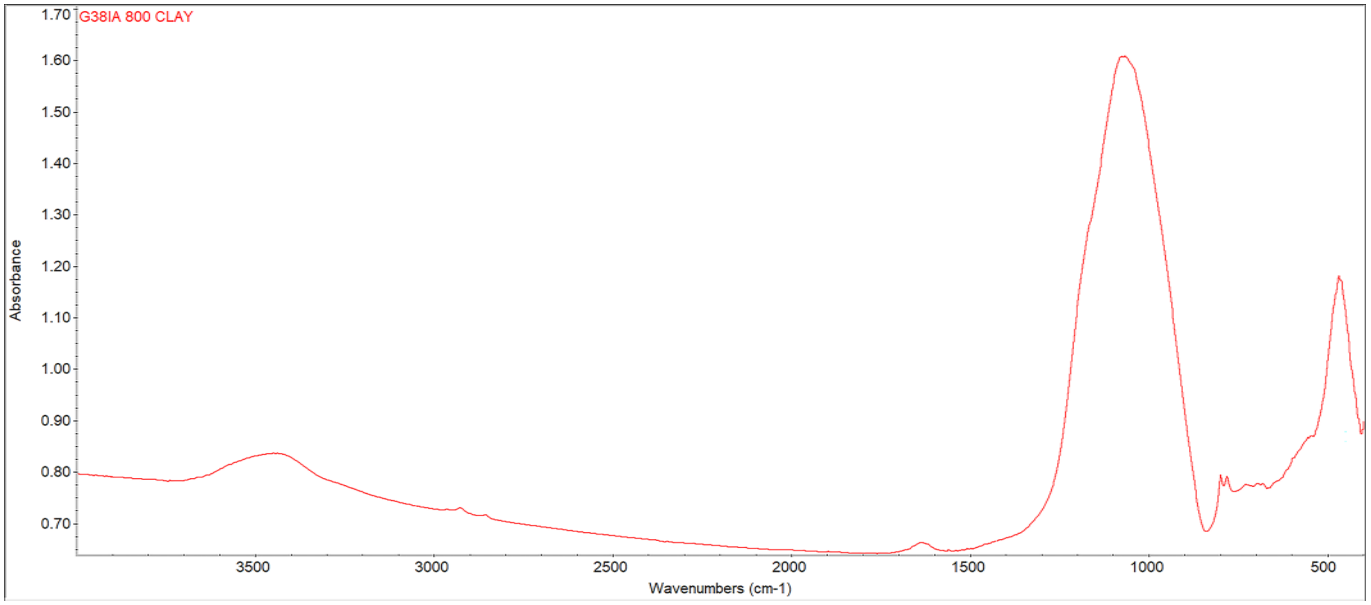


Fig. 14. FTIR spectrum of fired clay at 800C (after Kimmel Center for Archaeological Science Infrared Standards Library, Weizmann Institute of Science).

mean that these were not used as additives, in fact these products could have decomposed over time making them invisible in the archaeological record and the use of organic additives cannot be completely ruled out (Ergenç et al., 2021; Lancaster, 2021).

5.3. Processing and recipes

Dry sieving by manual separation highlighted that lean mixtures were the most prominent with few exceptions, for instance Sample 41. The presence of lean mixtures is in line with the 'Roman' tradition (Lancaster, 2021). It can be suggested that this small amount of binder served to reduce the costs of manufacture. Lime-based binders need a lot of resources, both in terms of production process as well as man-power (DeLaine, 1997; 2021). The diverse range of particle sizes also confirms the need for less binder as the smaller particles would have filled the spaces between the larger ones (Ingham, 2011). Furthermore, this picture emphasizes that crushing/grinding and mixing were the main activities during aggregate processing as no careful selection of particles through sieving or sifting was practiced (Ingham, 2011). It is possible to observe that *Ceramic-rich type 1B, Volcanic-rich type 3C* and the majority of *Ceramic and pumice-rich type 2* mortars have been exposed to consistently greater crushing/grinding; in fact, the particle sizes appear to be finer throughout. Overall, the ubiquitous presence of lumps indicates poorly slaked and/or poorly mixed lime due to practices of hot-mixing, dry slaking or maturing (Elsen, 2006). These lumps do not indicate problems with burning as no under- or over-burnt fragments were observed.

Different recipe types are evident from petrographic examination with the *Ceramic-rich* and *Volcanic-rich* types being the most prevalent. Generally, the recipe types do not seem to be *strictly* correlated to function. However, some observations can be made. For example, *Pumice-rich type 4* can be mainly seen for bedding purposes. This might be due to the lightweight nature of this material, making it best suitable for the middle and top sections of the walls and doorways where they

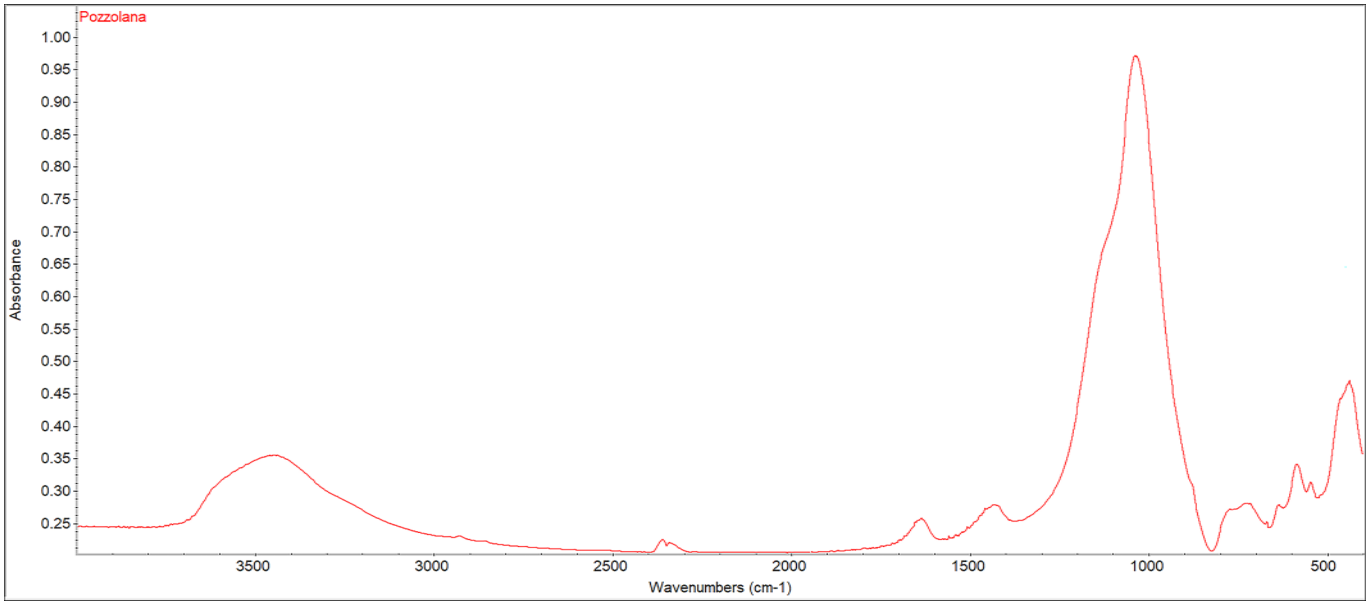


Fig. 15. FTIR spectrum of 'pozzolana' volcanic ash (after Kimmel Center for Archaeological Science Infrared Standards Library, Weizmann Institute of Science).

were used (Siddall, 2000). *Volcanic-rich type 3A* and *3C* are also predominant for general bedding functions, whether between brick or stone or in the bottom or top sections of the walls. The former mortar type is largely but not exclusively present in the Roman Imperial Bath-Gymnasium throughout time, while the latter seems to appear only in the structures of the Urban Mansion throughout time. Generally, *Ceramic-rich type 1A* and *1B* are mostly prevalent among floors. In the Urban Mansion spaces, it is important to note that the flooring samples underneath the presumable *opus sectile* floors of Room XLVI and the tesselate mosaic of Room L present the same *Ceramic-rich type 1B* recipe and impression surface treatments. These features correspond to the *nucleus* and the lime wash stratigraphy of Roman mosaic floors described by Vitruvius for the 1st century BCE (Caldeira et al., 2019). Additionally, another portion of the floor of Room L shows a *Volcanic-rich 3A* composition corresponding to the *rudus*. Hence, the inhabitants of Sagalassos might have more closely followed specific directions resulting in a fairly consistent practice of limewash-*Ceramic-rich 1B nucleus*-*Volcanic-rich 3A rudus* for the production of mortars for mosaic surfaces. These are also of the same building intervention suggesting that the same concoction could have been produced and applied in different nearby spaces. *Ceramic-rich type 1A* seem to be nonspecific, mainly present in the Roman Imperial Bath-Gymnasium for flooring but also for other purposes such as bedding. There seems to be a shift from *Ceramic-rich type 1A* in earlier phases to *Ceramic-rich type 1B* in later ones; however this is contentious as both recipe types are present in Sample 50. Spatial location might have influenced mortar recipes. This recurrence according to space could be due to the same building intervention and construction technology. Additionally, *Ceramic and pumice-rich type 2* seems a specific concoction used in the hypocaust system below Caldarium 1 for bedding purposes, specifically between pillars and walls. This group has better crushed/ground aggregate material for pillars and less crushed/ground aggregate material for walls.

The decorative wall plaster fragments from the Urban Mansion seem to show a recurring use of the same mortar types, namely *Volcanic-rich type 3B* and *Lump-rich type 5*. This could be due to function and/or space as the context of all these loose and *in situ* wall plaster fragments is still contentious. It is evident that these two mortar types constitute the rough or inner coat (Type 5) and the painting or outer coat (Type 3B). These samples differ from what has been illustrated in the ancient descriptions of Vitruvius (1st century BCE) and Pliny the Elder (1st century CE) (Lancaster, 2021; Pecchioni et al., 2008; Salvadori and Sbrolli, 2021; Weber et al., 2009). First, there are only two successive layers as opposed to six or seven outlined by the ancient authors. An explanation could be that this practice and expertise was lost through time, in fact the examined samples date centuries later than the ancient textual descriptions in question. Finally, the number of mortar layers was possibly decreased because Sagalassos was a peripheral Roman city (Salvadori and Sbrolli, 2021; Urosevic et al., 2023). For instance, up to two plaster layers are also attested at the Roman sites of Ephesos and the Sinop Balatlar Church Complex in Anatolia (Bakiler et al., 2016; Weber et al., 2009). Second, the use of marble or marble dust was not observed. This coupled with the fact that marble inclusions are rarely seen could mean that marble was not specifically imported or recycled for mortar materials. Finally, the rough coat layer is peculiar, in fact it is entirely made of lime lumps. This could point to an intentional adoption of lime lumps resulting from material processing for either practical or stylistic purposes.

6. Conclusion

This study on mortars from the Roman Imperial Bath-Gymnasium and the Urban Mansion at Sagalassos provides a better understanding on the construction and building technology of the ancient city. Overall, mortar production at Sagalassos shows a degree of standardization as well as variation. The former can be seen by the regular employment of lean mixes, lime-based binders and adoption of ceramic and volcanic materials. The latter is evident as at least 5 different mortar recipes were used according to textural and compositional features. In addition, recipe subtypes and unique samples can be discerned, highlighting that there is a departure from the major recipe types. Thus, it appears that the production of mortars was following broad directions rather than strict procedures and it developed from empirical knowledge, experimentation and possibly different and/or unspecialized workmanships.

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CRediT authorship contribution statement

Matilde Quilici: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jan Elsen:** Writing – review & editing, Supervision, Resources. **Inge Uytterhoeven:** Writing – review & editing, Resources. **Bas Beaujean:** Writing – review & editing, Resources. **Patrick Degryse:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104674.

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