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Mineralogical and physical–chemical characterisation of Roman mortars used for monumental substructures on the Hill of San Antonio, in the Roman city of *Italica* (prov. *Baetica*, Santiponce, Seville, Spain)☆

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ABSTRACT

The Roman city of Italica (Santiponce, Seville, Spain) is characterised by the use of *opus caementicium*, especially in major public works. Many of these works appear to be connected with the expansion carried out in the early 2nd century CE, a period in which this technique attained high levels of technical achievement. Traditionally, this expansion has been regarded as the personal initiative of the Emperor Hadrian, whose family roots were in the city.
The structure chosen for our case study is unique. It is located on the eastern slope of the so-called 'Hill of San Antonio' and has been interpreted as a substructure, or platform, for a public area above. However, the archaeological characterisation of this structure is still limited.
The mortars used in this construction have been characterised through petrographic, mineralogical, geochemical and physical analysis. Their mineralogical composition has been analysed using thin sections, XRD and SEM. Chemical composition has been analysed by XRF. Physical properties analysed include granulometry, density, porosity, porosimetry, mechanical and hydraulic properties. Following the analyses, four types of mortar were distinguished. In all cases, their composition is lime-based and includes different proportions of other materials, such as metamorphic, igneous and sedimentary rock. In general, a planned and consistent production technology can be inferred, as shown by the careful selection of raw materials, the proportion of *caementa* and the homogeneity of the resulting mortar.
The analyses have provided us with important information on the way the material was prepared and used depending on the structural needs of the construction. In addition, ancient mortar is in itself a valuable historical document concerning technological capabilities and choices and their degree of development at any given time, in this case, the Early Roman Empire.

1. Introduction

For several centuries now, the Roman city of Italica (prov. *Hispania Vlterior Baetica*, currently Santiponce, Seville) has attracted the interest of excavators and historians alike, which has resulted in an extensive bibliography (see Caballos et al., 1999 for syntheses, and Caballos, 2010 and references therein). Its present state is the result of a series of historical accidents, such as the construction, in the early 17th century, of the town of Santiponce on top of the earlier domestic quarters of the city. For this reason, the best-known sector of the city corresponds with the sophisticated area built to the north of the old city in the 2nd century CE. Based on the written record, this expansion has been linked with Hadrian, whose origins, like his predecessor's, were in the city; family links which have been related to other urban and architectural expressions in the city (Fig. 1).

In any case, the city's refurbishment also affected the old sector, inhabited since Republican times. The structure chosen for our case study is located in this sector. The structure can be described as a large platform built in *opus caementicum*, constructed on the so-called Hill of San Antonio (Fig. 1.1, 2 and 3). It is likely that the function of this platform was to support a major architectural complex, which is generally interpreted as a large porticoed square presided over by a central religious building. Around the beginning of the Christian era, the eastern slope of the hill was used for the construction of the theatre seating area. Due to the proximity of these structures and the lack of specific studies, they have often, and erroneously, been regarded as a single complex – starting

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Fig. 1. Aerial view of the Roman city of Italica. The numbers point to the structure which we analyse in this work (1) and other locations cited in text: *tetrapylon* (2), 'greater' baths (3), sewer (4) and 'lesser' baths (5).

with the earliest excavators (Luzón, 1982). New findings, however, have demonstrated that they belong to two completely different construction projects and that their construction dates are more than a century apart (Pellicer et al., 1982; Jiménez Sancho et al., 2013). Naturally, this does not mean that the newest construction encroached in any way upon the earliest, or that both could not have been used simultaneously for centuries.

This is not the only *opus caementicium* substructure in the city, but it is certainly the largest one that has been preserved. For example, direct observation has also revealed the use of this technique in the so-called '*tetrapylon*' (Fig. 1.2), the 'greater' baths (Fig. 1.3), and the sewer that runs beneath the eastern *decumanus* (Fig. 1.4); all have *opus caementicium* walls with the imprint of vertical side-shuttering. All of these structures are dated to the 2nd-century expansion. This technique, although there are considerable differences in terms of material and finish, is also found in the so-called 'lesser' baths (Fig. 1.5), which are traditionally dated to the reign of Trajan (Roldán, 1993, 121–131; Bukowiecki and Dessales, 2008).

The platform on the Hill of San Antonio has been chosen for this study owing to its monumental character, its excellent state of preservation and the use of a construction technique which is characteristic of the city during Hadrian's reign. This analysis of the mortars has a twofold objective: to understand the function of the structure by identifying differences within it, and to characterise the mortars in order to compare them with those used in other constructions, both in the city and in the broader Roman Empire, especially in the Hadrianic period, for instance the substructures built on the north-eastern slope of the Palatine Hill, in the Villa Adriana and other construction projects in Greece (Fink and Wech, 2013).

One of the most important factors to be taken into account in the study of *opus caementicium*, mortars and the combination of both, is the twofold nature of these materials, which are at the same time construction material and construction technique. Their 'nature' as a construction technique is especially obvious when used by itself and not in combination with others on visible surfaces; in this work we shall focus on this use, as we are especially interested in *opus caementicium* as a construction technique. Theoretically, Roman concrete was made of sand and different sizes of clastic rock fragments, slaked lime and pozzolan, preferably volcanic granular ash; the volcanic ashes could, if necessary, be replaced with pulverised pottery fragments or clay (Oleson et al., 2004). The lime and other additions gave the mortar the desired mechanical properties, essentially density and flexibility, as well as the hardness of the end product. Mortars were especially suited to the construction of walls and vaults. The *caementa* that were added to the mix could be of a considerable size, as major *opus caementicium* structures, like that which we are analysing here, clearly demonstrates. For instance, large inclusions increase the resistance and load capacity (Lamprecht, 1985, 21 ff.). Generally, the raw materials used for the production of mortar were obtained from nearby sources and, if local conditions allowed, even the soil on which the building was going to be built. Ultimately, the quality of the mortar depended on the choice of materials and the way they were combined,[1] which changed depending on the desired properties of the end product.

This work focuses on the analysis of the materials used in the platform, which is of enormous interest concerning construction technologies in Italica during Hadrian's reign. To date, this material has not been subject to archaeometric analysis,[2] and construction technologies in the city are poorly understood.

2. Historical and archaeological context

2.1. Background and context

Significant sectors of the ancient Roman city of Italica are currently open to the public. It is under the administration of public heritage bodies belonging to the Comunidad Autónoma (Autonomous Region) of Andalusia (Izquierdo, 2012, 39–50) (Fig. 1).

[1] Vitruvius (2.5.7) suggests the proportions to be used according to the nature and origin of the raw materials in use.

[2] The exception is a brief low-resolution study in Roldán (1993, 308–309), where the percentage of carbonates (27%), silicates (38%), lime (7%) and clays (28%) in a series of urban buildings is given; the San Antonio platform is represented by sample 9 (ITA.7.2).

Fig. 2. View of the Hill of San Antonio and theatre, located on its eastern slope. The arrow points to the foundations which are the subject of this work, immediately to the west of the theatre.

For several centuries, Italica has been subject to archaeological work carried out according to more-or-less scientific parameters, and today several areas of the city lie exposed. As previously noted, the best known of these sectors is the result of a city expansion which occurred during the reign of Hadrian in the early 2nd century CE. The foundation of the Roman city, built on the location of a pre-Roman settlement, goes back to the late 3rd century BCE. Unfortunately, the oldest areas of the city are situated under the modern town of Santiponce. Therefore, excavation of the Republican and Early Imperial city has only been possible in a few isolated and disjointed locations, including the theatre and its surrounding areas (Jiménez Sancho et al., 2013) (Fig. 2). The structure which prompted this study is situated above the theatre (Rodríguez-Gutiérrez, 2004, 273-277) (Fig. 3).

With the beginning of excavations in the area of the theatre in the 1970s, a series of substantial *opus caementicium* structures began to emerge. At first, following some influential works on theatre buildings, such as that of Traversari (1960), Italica's archaeologists interpreted these structures as pertaining to large water deposits related to the theatre. Their fill was thus assumed to be of modern date and excavated unsystematically (Luzón, 1982). For this reason, no stratigraphic record of any relevance exists. Unfortunately, buildings in this area, including the top tier of the theatre backdrop (*summa cauea*), are only preserved at the foundation or substructure level. Because of this, the relationship of the extant structures with the different urban projects in this area is unclear, as is the way each project related topographically with its predecessors.

The dimensions and date of the Hadrianic structures were first explored during a stratigraphic excavation carried out in 1977 in an urban plot known as Calle Moret 15 (Pellicer et al., 1982; Pellicer, 1998, 150–151). This excavation demonstrated the platform's structural independence from the theatre. It was dated to the late 1st and the early 2nd century CE. In the 1980s, the area was subject to new excavations during the restoration works related to the integration of the theatre into its urban environment (Rodríguez-Gutiérrez, 2004, 32–37). These excavations showed that the structure was much larger than hitherto expected: it continued to the west, under the modern houses. However, the area was turned into a terrace from which it is possible to view the theatre from above, and was levelled with large amounts of modern rubble. This has obscured many of the original elevations and the relationships between different structural elements. In any case, these works, not all of which are published, demonstrated that the structure must be dated to the early 2nd century CE, although some authors suggest a date in the reign of Trajan (Corzo, 1993, 163-164) and others in the reign of Hadrian (Roldán, 1993, 83). The latter opinion is based on a comparison of the bricks used to build a pipeline which is integrated into the construction, with other bricks found elsewhere in the city.

Additionally, some of the most singular pieces of Italica's statuary (Venus, Mercury, Diana) were found in the immediate environment of the structure. These pieces formed a coherent whole, which could be associated with the decoration of a place of significance for the city (León, 1995; Rodríguez Hidalgo and Amores, 2009). Owing to its substantial dimensions and its technical features, the platform has been subject to considerable scholarly attention (Roldán, 1993, 78–79; Rodríguez-Gutiérrez, 2004, 273–277; Ahrens, 2005, 64; Jiménez Sancho, 2012, 122). In general, all authors seem to agree on a key point: its identification as a large terrace on which a public space existed.[3] At its eastern end, the structure must have had a peculiar appearance in order to adapt to the eastern slope of the Hill of San Antonio.

In recent years, once more in connection with works aimed at recovering and presenting the theatre and its surroundings, a number of small-scale archaeological excavations have been carried out, which has increased our knowledge of the position of different elements within the complex, as well as the construction techniques used (Rodríguez-Gutiérrez and Jiménez Sancho, 2009; Jiménez Sancho et al., 2013, 276–278). It has thus been recognised that the walls were built by lost-shuttering and the foundation trenches were dug through existing structures when necessary. Macroscopic observation is sufficient to allow us to note the implementation of different

[3] Riskier proposals, nevertheless, exist, such as the association of the platform with the enlargement of the capacity of the theatre (Ventura, 2006, 103, n. 7), which seems unlikely due to the height of the *cauea*'s back wall.

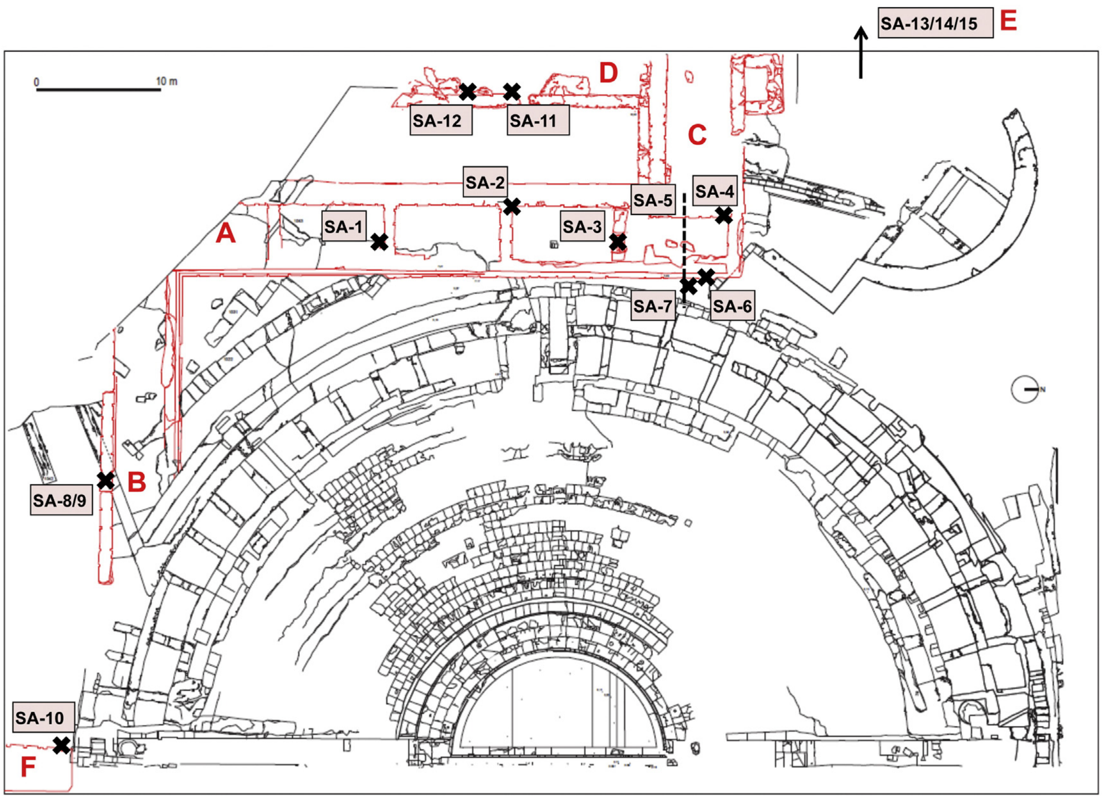

Fig. 3. Drawing of the archaeological features identified on the Hill of San Antonio, with an indication of the sectors and sampling points mentioned in the text (IT.SA.13, IT.SA.14 and IT.SA.15, in zone E, fall outside the margins of the map (ca. 2 m to the west).

technical solutions. Among them, for example the inclusion of brick fragments in some areas (Fig. 3D) as well as the combination of *opus caementicium* with other techniques, for example triangular-brick brickwork not found elsewhere in the city.

2.2. The structures

Before we undertake the architectural analyses of the preserved structure (Fig. 3), it must be clarified that it is only partially visible, and therefore susceptible to examination. The full structure must have occupied a good deal of the Hill of San Antonio.

The complexity of this substantial structure responds to its purpose, which was to support the slope and to give it a clear-cut edge. The hill was by then a sort of urban tell formed out of the deposits which had been building up since the Republican period (Rodríguez-Gutiérrez and Jiménez Sancho, 2009; Jiménez Sancho, 2012, 106; Jiménez Sancho et al., 2013, 278–280). This suggests that the builders had a precise knowledge of the area and of the architectural events that had taken place in it.

The best-preserved sector, fully built in *opus caementicium*, corresponds to two parallel walls, 1.20 m thick and 4.40 m apart (Fig. 3A). These walls are joined by five perpendicular walls, the thickness of which measures between 0.60 and 0.90 m, forming rectangular 'boxes' which are 8.20 m wide. The main walls ended at different elevations, and the struts slope accordingly. The 'boxes', filled with earth, were covered with a thick lid of *opus caementicium*. The lid also sloped towards the east and formed a sort of ramp. At the north and the south ends, the structure forms a right angle (Fig. 3B and C). Two sets of walls, similar to the main north to south ones, but lacking intermediate struts, project towards the west (at the northern end) and the east (at the southern end). To the south, however, some singularities exist, but these are hard to examine in detail because they run under the nearby houses and because they are partially covered by the recent fill

Table 1
Description of samples (Fig. 3).

COD samples	Description/location
IT.SA.1	*Opus caementicium* from the eastern-oriented oblique platforms. Lime mortar.
IT.SA.2	Whitewash layer and calcareous crust found on the shutters located in the join between the longitudinal and transversal walls.
IT.SA.3	Mortar from the buttress walls on the retaining walls. Sample taken from the interior of the walls, which have been cut across.
IT.SA.4	Whitewash layer and calcareous crust found on the shutters located in the lateral walls, which were plastered.
IT.SA.5 a–f	Mortar from the exterior surface of the terrace's retaining wall. Six samples taken at different elevations.
IT.SA.6	Whitewash layer, with calcareous crust and remains of mineralised timber.
IT.SA.7	Whitewash layer, with calcareous crust and remains of mineralised timber.
IT.SA.8	Mortar from the southern wall, taken from the interior of the walls, which have been cut across.
IT.SA.9	Granite *caementa* located near the sampling point IT.SA.8.
IT.SA.10	Mortar from the so-called 'Wall of San Antonio' (WSA).
IT.SA.11	Mortar from the westernmost structures of the complex, at the current panoramic terrace.
IT.SA.12	Mortar from the westernmost structures of the complex, at the current panoramic terrace.
IT.SA.13	Mortar from the lower E–W retaining wall.
IT.SA.14	Lime nodule from the same mortar as sample IT.SA.13.
IT.SA.15	Mortar from the upper E–W retaining wall.
IT.TEA.1	Mortar from the theatre seats foundations.
IT.TEA.2	Mortar from the theatre seats foundations.
CMA.1	Sample of blue marl (geological level) on which Italica stands (coord.: 37.441052, −6.043037).
CC.1	Sample of calcarenite from the same location as sample IT.SA.3. (*caementa*).
CCG.1	Tortonian calcarenite from Lora del Río (Guadalquivir Valley). *Ermita Setefilla* quarry (coord. 37.703464, −5.497884)

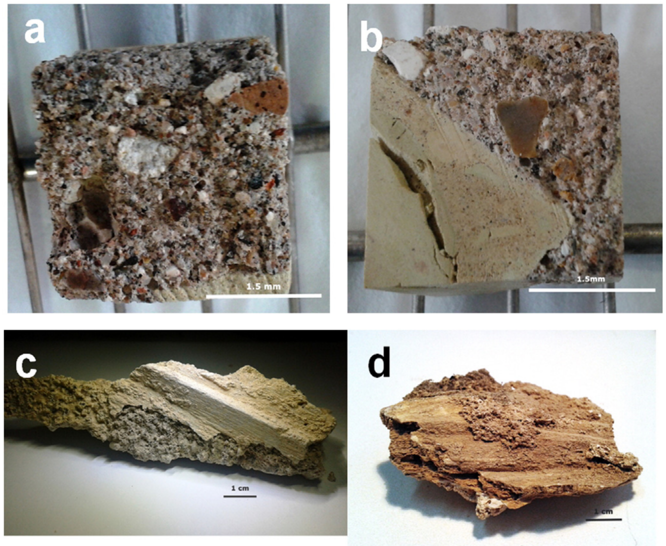

Fig. 4. a. Mortar corresponding to the braces; b. presence of lime nodules in the mortar; c. surface layers; d. calcareous crust found in different surface areas; these crusts correspond to the, now mineralised, pieces of timber used as shutters.

which is associated with the creation of the modern panoramic terrace. Moreover, this situation has affected sample collection and, therefore, the whole analytical process. Despite the regularity of the construction techniques, in a north-south wall, parallel to the first ones described, located to the west, a large number of sizeable brick fragments are present in the *caementa* (Fig. 3D), suggesting this wall was built at a later date. This hypothesis also seems to find confirmation in the structural relationships. Unfortunately, this sector is currently covered below surface level, so no in-depth characterisation has been possible.

Other features visible in the vicinity of the hill have also been identified as part of the structure, for example an exedra (Fig. 3E) identified during a rescue archaeological excavation on the northern slope of the hill (corresponding to 19 Calle Feria of the village of Santiponce) (Jiménez Sancho et al., 2013, 281–286). Traditionally, the exedra has been associated with a supposed Augustan wall that, in fact, has never been found in this area. This adds further weight to the notion that the platform supported a large open public space, the sides of which would have been equipped with exedrae, like the neighbouring and well-known *Traianeum* (León, 1988). Finally, a structure identified on the opposite side (Fig. 3F) has often been described as the easternmost feature of the complex. This structure is commonly known as the *Muro de San Antonio* (Wall of San Antonio — hereafter WSA). Although it shares some characteristics with the nearby structures, some technical differences demand a cautious approach to this affiliation (Rodríguez-Gutiérrez, 2004, 275). In fact, recent archaeological works seem to confirm that its identification with the platform is not quite as straightforward as it once seemed (Jiménez Sancho, 2012, 119–120).

In conclusion, the virtual entirety of the structure, or at least the parts of it that are visible today, was built in *opus caementicium*. The construction technique started with the digging of a trench; afterwards, shuttering was laid out to line the interior walls, using vertical wooden panels linked by horizontal ones. These panels were not recovered afterwards, and their print has been splendidly preserved to an approximate height of 0.18–0.20/0.40 m. Some of these shutters were as long as 3.20 m. The *caementa* used were diverse, but small- and medium-sized calcarenite fragments are predominant, along with some granite clasts and fragments of brick and *tegulae*. Macroscopic analysis of the mortar base reveals a fine sand- and lime-rich mix, but a more precise characterisation of components and proportions can only be achieved through analytical work.

3. Materials and methods

3.1. Materials

3.1.1. Sample selection

As previously noted, only a small part of the platform has been excavated to date. Our sampling followed a careful strategy designed in order to answer a number of specific morphological and structural questions concerning the following points (Fig. 3 and Table 1):

- *The composition of mortar in different structural elements*. The objective was to determine the composition of supporting walls, transversal struts, oblique platforms, fills, 'whitewash' layers, and calcareous crusts. Different functions may have involved different choices of raw materials and different proportions, as well as the application of different construction techniques.
- *The homogeneity of the mortar*. In order to determine the degree of homogeneity of mortar, different samples located at different heights within the same features were taken. These vertical sample lines reveal whether a hierarchy of materials was followed when building the structure. Sampling different depths within the walls would have been equally interesting, but the excellent state of preservation of the walls has prevented sampling, except in a few places where transversal cuts existed.
- *Mortar comparison along structures*. Selection of samples from other buildings erected using similar techniques (especially foundations)

Table 2
Mineralogical composition of samples.

Sample	Quartz	Calcite	Albite	Feldspars K	Phyllosilicate	Mica	Anphibole	Other	Proportions (weight) added lime
IT.SA.1	23	15	5	1	51	Trace	3	Po & To	1:4
IT.SA.2	30	44	7	3	13	Trace	2	Dol	1:2
IT.SA.2A	13	81	Trace	–	0	–	–	Dol	4:1
IT.SA.2B	38	26	16	4	Trace	12	2	Dol	1:3
IT.SA.3	70	17	4	2	0	Trace	6	Dol & trace of Gp	1:4
IT.SA.5f	41	30	3	3	20	Trace	Trace	Dol	1:3
IT.SA.5fA	22	18	6	2	42	Trace	–	Dol (10%)	–
IT.SA.7	16	38	2	2	36	Trace	–	Dol & Arg	1:2
IT.SA.10	16	19	5	2	54	Trace	1	Dol & Po	1:4
IT.SA.10A	21	16	2	1	52	Trace	3	Dol & Gp	–
IT.SA.14	5	94	2	3	0	Trace	–	Dol & Po	–
IT.SA.15	55	22	9	6	3	Trace	2	Trace of Gp	1:4
IT.TEA. 1	50	11	9	4	22	Trace	4	Dol	1:4
IT.TEA. 2	52	15	9	4	16	Trace	4	To & Dol	1:4
CMA.1	19	16	3	Trace	58	Trace	–	Esm, Dol & Gp	–

The codes in the left column correspond to the samples described in Table 1. Letters A and B indicate that the part of the sample which was subject to mineralogical analysis had special characteristics, as follows: IT.SA.2A: concretion of mineralised timber; IT.SA.2B: whitewash layer, under calcareous concretion; IT.SA.5fA: clayey nodule; IT.SA.10A: clayey nodule. Other references: Po: portlandite. To: tobermorite. Gp: gypsum. Dol: dolomite.

or at a similar date. In this case, samples were taken from the foundations of the *summa cauea*, in the theatre, and the WSA.
– *Identification of sources for the raw materials*. In this regard, the geological analysis has focused on the alluvial material from the Guadalquivir Basin and the Baetic System in the vicinity of the site, specifically Tertiary and Quaternary materials.

As shown in the table, most samples were of mortar, and were taken from the external face of the walls, to a maximum depth of 0.10 m (Fig. 4a and b). Wherever possible, for example where the modern buildings cut through the structure, samples have also been taken from the interior of the walls. Finally, some of the samples correspond to a rather interesting feature: in some places, a very fine and thin layer (barely a few millimetres thick) of a sort of whitewash formed between the shutters and the *opus caementicium*. This whitewash may also be observed alongside a series of calcareous crusts which correspond to the mineralised wood (Fig. 4c and d). An analysis of these concretions is of enormous interest, as they can be very revealing, as we shall see shortly, with regard to the mechanical and technological processes involved in the construction of the structure, apart from those generated as result of the remobilisation of carbonate-rich fluids processes after deposition. It seems likely that, originally, this layer covered the whole surface of the walls, but erosion and wear have washed it away, especially in the most exposed areas.

In addition, the Blue Marls Units (IGME, 1975) on which the city of Italica stands has also been analysed in order to compare the marl with the clayey nodules that appear in the building material. Finally, the preliminary analytical results prompted the analysis of the Tortonian calcarenite that exists around the margins of the Guadalquivir valley in the vicinity of Seville (Lora del Río), as a candidate raw material in these constructions.

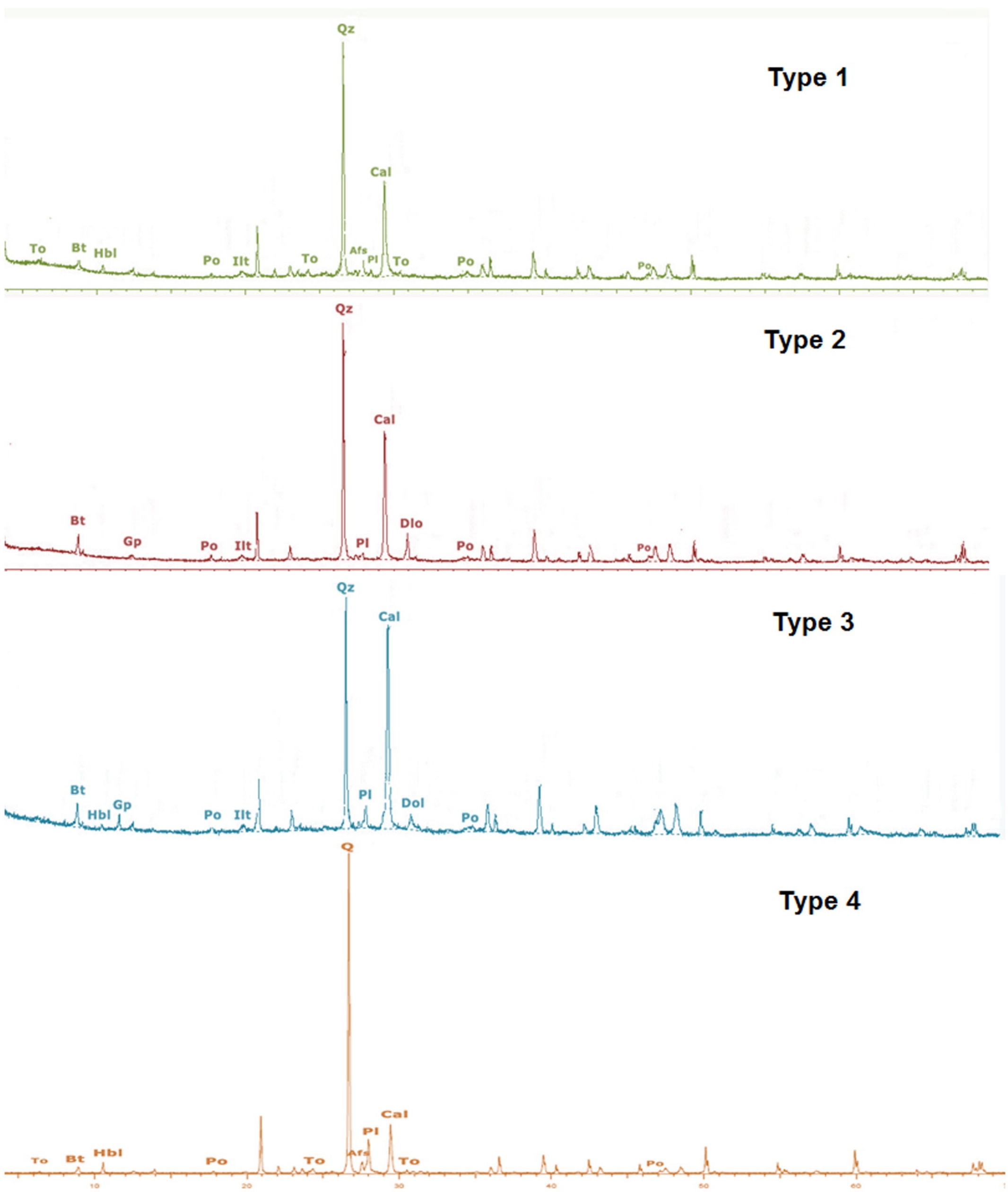

Fig. 5. XRD patterns of the Roman mortar matrices.

3.2. Methodology

The mineralogical composition of the materials was evaluated by X-ray diffraction (XRD), using a D8I 90, BRUKER diffractometer with copper anode tube. Standard semiquantitative method ($\Delta 2\theta = 3$–$70°$; step = 0015°; $t = 0.1$ s; tube conditions: 40 kV and 30 mA; divergence slit: fixed 0.5°; turn 30 rpm; and niquel filter in the tube. Duration: 6 min 54 s). The chemical analysis of major and trace elements was carried out using the Phillips X-ray Fluorescence (XRF) minitrace method, and a PANalytical AXIOS Rh spectrometer (CITIUS, Seville University). Thin sections were vacuum impregnated with an epoxy resin/hardener. They were polished to a standard thickness of 30 μm, covered with a glass slip and examined with a Leica DMLP petrographic polarising microscope and camera, and a Leica DFC 280 (IAPH) digital image capture system. A scanning electron microscope (SEM)-FEI Jeol 5400× (IAPH) was used to analyse the microstructure, particle morphology and texture relationship.

Sieve Analysis followed standard UNE-EN 933-1:2012, using sieve series UNE 7050, which is similar to ASTM C33-85. Samples were first treated with HCl (in HCl solution: H_2O 1:1 HCl 37% in a proportion of HCl:H_2O 1). Grain-size distributions of the aggregates were determined by using sieves measuring 0.063 mm, 0.08 mm, 0.125 mm, 0.5 mm, 1 mm, 2 mm, 2.5 mm and 10 mm, and were also used for the calculation of Cc (coefficient of curvature) and Cu (coefficient of uniformity). The coefficient of uniformity is a parameter that evaluates the homogeneity in the particle size in accordance with the following formula:

$$\mathrm{Cu} = \frac{\mathrm{D60}}{\mathrm{D10}}.$$

D60 and D10 refer to the opening of the sieve when 60% and 10% of the particles are still being retained. A high value, therefore, indicates that D60 and D10 particles vary greatly in size. A Cu < 5, for example, indicates uniform soils.

Cc evaluates the progression in the variation in size of soil particles, and, therefore, the gradation of different particle size ranges. It is calculated with the following formula:

$$\mathrm{Cc} = \frac{\mathrm{D30}^2}{\mathrm{D10} \cdot \mathrm{D60}}.$$

In well-gradated soils, this parameter has a value between 1 and 3, which indicates that there is an ample range of sizes and significant quantities of intermediate-sized particles.

These curves have been compared with Fuller and Thompson (1907) ideal standard, which is based on the compaction capacity of particles in a given volume, which indicates maximum density.

Real density was obtained with a helium pycnometer (pentapycnometer 5200e), which measures the precise volume of a solid sample following Archimedes' principle and Boyle's law. Bulk density and water porosity have been calculated by hydrostatic immersion. Hg porosity and pore distribution have been analysed by mercury intrusion porosimetry (Pore Master 60 GT). Measured size ranges go from 1.000 to 0.001 μm, including low pressure (0.2–50 psi) and high pressure (20–60,000 psi) readings. This technique allows for the determination of pore size (radius or diameter), using Laplace's equation and the structure of capillary tubes in porous media. In both cases, volume and pressure have been compared using Poremaster software (CITIUS, University of Seville).

The investigation of mechanical (compressive strength) and hydraulic properties requires large samples, which in our case could be secured from mortar types 1 and 2. Standard UNE EN 1015-11 (2000) was followed, using CODEIN-mod MLO-30 (Laboratory Faculty of Architecture, Seville) with cubic samples (3x3x3 cm) (instead of the standard-recommended size owing to the limited amount of sampling material available) at a velocity of 1 kgf/s, as well as recommendations (RILEM, 1980) for the determination of free water absorption and desorption.

4. Results

4.1. Mineralogical and geochemical composition of mortar

One of this work's main objectives was to identify the provenance of the raw materials and to investigate the construction techniques used.

In mineralogical terms, the mortar (Table 2, Fig. 5) is primarily composed of quartz, calcites and phyllosilicates; altered biotite-type mica and clay-minerals are predominant among the phyllosilicates. Minor components include feldspars, amphiboles and, in some samples, trace amounts of tobermorite, dolomite, portlandite, CaO, aragonite and variable proportions of gypsum. They are lime mortars with some degree of hydraulicity, in which most of the calcite content can be related to the addition of lime, which appears in a proportion in weight of 1:4 in mortar and of 1:2 in whitewash.

Portlandite and calcite are commonly found in lime-rich mortar: calcium carbonate often appears in the form of aragonite or vaterite (Lubelli et al., 2011). Tobermorite is a calcium silicate hydrate that can appear as a result of the reaction of lime with natural pozzolan components (Jackson et al., 2013), but also as a result of the reaction of lime to

Table 3
Major components (%).

Sample	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3	Cl	IL
IT.SA.1	40.0	6.2	2.0	0.0	3.3	23.9	0.8	1.3	0.2	0.1	0.1	0.1	21.0
IT.SA.3	59.1	6.0	1.6	0.0	1.0	14.5	1.1	1.8	0.2	0.1	0.3	0.8	13.4
IT.SA.5d	49.3	5.4	1.5	0.0	3.8	17.7	0.7	1.2	0.2	0.1	0.1	0.7	19.0
IT.SA.5e	49.61	5.65	1.63	0.04	1.05	13.02	0.56	1.71	0.13	0.08	0.1	0.3	25.4
IT.SA.5f	38.8	8.0	2.6	0.1	2.0	21.1	0.4	2.3	0.4	0.1	0.1	0.7	23.13
IT.SA.5fA	39.50	8.50	2.79	0.06	2.04	20.55	0.41	2.30	0.42	0.14	0.07	0.4	22.23
IT.SA.7	15.23	3.14	0.83	0.02	1.45	39.25	0.20	0.94	0.12	0.42	0.18	0.1	37.22
IT.SA. 10	58.5	4.6	1.6	0.0	1.0	9.6	1.0	2.7	0.2	0.1	1.4	0.4	18.3
IT.SA.10A	38.10	7.96	2.53	0.05	2.42	16.63	1.01	3.79	0.33	0.14	0.70	5.0	25.35
IT.SA.11	50.4	6.2	1.9	0.0	2.2	19.2	1.2	1.6	0.2	0.2	0.1	0.2	15.8
IT.SA.12	50.0	6.2	1.8	0.0	1.0	17.0	0.7	2.2	0.2	0.3	0.2	0.3	19.6
IT.SA.13	44.1	5.6	1.6	0.0	1.5	20.9	1.3	2.1	0.2	0.1	1.4	0.2	20.2
IT.SA.14	5.8	0.7	0.2	0.0	0.4	47.5	0.4	4.1	0.0	0.0	0.4	0.6	39.46
IT.SA.15	48.4	6.4	2.0	0.0	4.3	15.8	1.3	2.1	0.2	0.1	0.3	0.2	18.2
IT.TEA.1	61.88	8.70	2.23	0.05	1.22	10.69	1.35	1.55	0.27	0.12	0.10	0.1	10.84
IT.TEA.2	57.94	7.50	1.94	0.04	1.54	13.89	1.47	1.65	0.22	0.10	0.12	0.3	12.58
CMA.1	40.27	10.27	3.64	0.07	2.09	17.55	0.30	2.03	0.42	0.04	0.04	0	22.1
CC.1	24.87	4.15	1.27	0.07	0.48	40.02	0.10	0.89	0.14	0.19	0.03	0.01	26.31
CCG.1	16.56	0.79	0.29	0.19	0.18	48.82	0.07	0.19	0.03	0.23	0.04	0.66	31.61

IL: ignition loss.

brick dust. This is characteristic of Roman mortar when the geological environment is lacking in this natural component (Oleson et al., 2004). The reaction occurs in the clay-matrix interface and depends on both the type of clay and the proportion of lime in the mortar (Silva et al., 2006). This component is generally amorphous in nature and difficult to detect by XRD (Haga et al., 2002).

The nodules present in these mortars are primarily clayey in nature (65%), and to a lesser extent quartz, calcite and gypsum (in trace proportions) are also present, which fits well with the Blue Marls Units of the geological substratum (Galán and Pérez, 1989; Tsige and Gonzalez de Vallejo, 1996; Borja et al., 2012, 85-87) of the building and the city in general; blue marl is characteristic of the Miocene substratum throughout the Guadalquivir valley.

Some exceptions exist: the predominantly clayey mortar sampled in the WSA (IT.SA.10) have a higher gypsum and phyllosilicate content (>50%). This suggests that the soil on which the wall was built, instead of river sand, was used in the construction of this feature. Also, the foundations of the theatre's *summa cavea* (IT.TEA.1 and IT.TEA.2) are very similar to the samples from Area A in mineralogical terms, although, as we shall see presently, they are different with regard to other parameters. In any case, they have a smaller proportion of phyllosilicates, due to the absence of clayey material, a high quartz and feldspar content (higher proportion of aggregates) and a more crystalline binder.

An analysis of the chemical composition of the mortar (Table 3) reveals a high proportion of SiO_2 (50%) and CaO (15%), which fits well with the mineralogical data obtained by XRD and lime: aggregate ratio in weight (1:4). The higher level of CaO observed in the whitewash and calcareous crusts, therefore, is related to a higher proportion of calcite. In the samples from the WSA there is a higher proportion of sulphates, similar to the gypsum content detected by XRD.

The trace elements detected are similar in all samples. The differences are due to the variety and heterogeneity of the aggregates; similarly, variation margins are related to the well-sorted granulometry, as we shall see presently. However, the considerable variations in the values presented by several elements in different samples (Table 4) reveal the limitations of the approach. For this reason, it seems that a statistical processing of data cannot offer a sufficiently significant picture. The high chloride, Pb and Cu content detected in the WSA are probably due to the considerable degree of exposure to modern constructions that this structure has had: in some areas, in fact, remains of Portland cement and modern paint can still be detected. Arsenic content is likely due to the administration of biocides, which are often used to sanitise the sector.

Petrographic analysis has allowed for the identification of differences between the different mortar sampled, but has also confirmed the use of similar raw materials: river pebbles and other raw materials from the nearby southwest river bank (Fig. 6). These materials are to be found in the undifferentiated quaternary terraces in the NW corner, which include sandy layers, a large number of quartz river pebbles, feldspars and igneous and metamorphic sub-rounded and sub-angular rock fragments dating to the Palaeozoic period (Ossa Morena, Iberian Massif), along with the remains of resedimented blue marl (IGME, 1975) and calcarenite. The generalised use of clayey nodules of irregular size (sometimes over 1 cm), in proportions of up to 30%, has been confirmed. This high proportion suggests that they may have been added deliberately. (See Fig. 7.)

In addition, the analysis detected the absence of organic matter and the presence of ceramic fragments of irregular size (between 0.5 and 2 cm in diameter). These can increase the mortar's hydraulicity when in contact with highly reactive lime, depending on their firing temperature, mineralogy, content during their amorphous phase and surface area (Shvarzman et al., 2002). The surface of pottery sherds are the most reactive to lime (Walker and Pavía, 2011), and lime increases the cohesion of aggregates and improves the mortar's mechanical properties (Tekín and Kurogöl, 2011) and resistance to environmental factors (Moropoulou et al., 2000).

Table 4
Trace elements (ppm).

Sample	As	Ba	Co	Cr	Cu	Ga	Hf	La	Mo	Nb	Nd	Ni	Pb	Rb	Sc	Sr	Ta	Th	Tl	V	U	W	Y	Yb	Zn	Zr
IT.SA.1	3.5	259.0	9.6	44.9	8.7	12.7	5.8	19.0	2.4	7.6	19.8	16.7	3.5	41.7	18.1	246.0	11.5	11.8	1.0	49.7	2.7	3.9	17.8	1.8	82.2	85.7
IT.SA.3	0.1	229.7	6.9	23.7	8.5	12.9	4.4	13.9	2.6	12.6	20.9	16.0	8.5	47.6	11.9	132.5	0.0	13.0	0.9	25.7	3.3	5.7	17.9	2.1	81.6	62.2
IT.SA.5d	0	244.9	11.0	17.8	20.4	13.3	5.2	17.9	2.3	6.0	20.7	15.6	1.1	39.7	12.4	138.0	5.2	10.8	1.0	37.1	2.6	3.7	17.2	2.0	79.3	72.8
IT.SA.5f	4.8	257.3	10.7	18.3	13.1	13.0	4.9	21.8	2.4	9.8	19.9	23.6	6.9	41.7	14.5	129.8	7.8	11.7	0.9	36.1	3.1	12.1	17.6	1.7	78.3	57.6
IT.SA.5fa	0.4	248.6	5.7	36.5	19.9	12.2	5.8	23.4	2.7	19.1	22.4	27.9	20.5	56.8	10.0	250.0	4.3	14.6	0.9	49.2	3.0	12.6	20.1	1.5	87.0	179.4
IT.SA.7	0.0	120.4	0.0	17.4	65.3	10.7	5.5	21.9	1.9	0.0	12.1	9.8	201.6	22.7	20.2	220.7	0.0	7.7	0.9	24.2	1.1	6.0	13.6	2.1	74.4	52.1
IT.SA.10A	23.6	209.5	9.6	43.8	14.2	12.8	5.4	18.1	2.8	24.0	17.4	22.3	20.9	49.9	11.7	220.7	0.0	14.9	1.1	56.1	4.4	4.6	20.2	1.9	86.0	104.5
IT.SA.10	0.0	138.2	8.9	37.0	17.4	13.8	6.8	20.5	2.7	16.1	18.8	16.2	4.7	39.6	9.7	117.9	6.9	13.9	1.0	41.9	3.0	9.9	18.3	1.8	79.2	64.2
IT.SA.11	3.4	244.0	8.8	25.9	48.0	12.7	5.0	27.5	2.4	8.3	13.9	22.2	45.3	50.1	11.5	190.8	4.5	10.5	0.9	44.2	3.2	7.0	17.3	1.9	135.7	124.0
IT.SA.12	10.1	261.2	7.9	19.7	29.8	12.8	6.0	20.9	2.6	15.7	19.9	22.2	27.0	51.7	11.5	156.4	0.0	11.8	0.9	33.8	2.3	7.8	18.2	1.7	92.8	75.1
IT.SA. 13	13.9	261.5	7.3	27.3	23.6	12.9	6.2	12.6	2.6	9.6	18.4	22.3	6.6	44.4	11.6	158.1	0.0	11.5	0.9	41.3	2.2	7.9	17.2	1.9	78.0	104.5
IT.SA.14	0.0	106.7	0.0	0.0	0.0	9.0	3.2	19.4	1.7	0.0	16.2	0.1	0.0	8.8	20.2	91.7	0.0.	3.1	0.7	11.0	0.0	0.0	11.4	1.9	52.2	28.1
IT.SA.15	1.8	243.8	9.8	19.9	8.0	13.8	6.4	18.3	2.6	13.0	23.8	18.7	21.6	48.9	9.6	154.0	0.0.	13.5	1.0	45.9	0.8	6.7	12.0	1.9	53.4	32.1
IT.TEA. 1	15.0	251.4	8.6	50.0	38.8	14.6	5.7	19.7	3.1	23.7	17.5	20.1	30.1	48.8	12.7	145.5	0.0.	17.8	1.2	48.6	4.8	5.7	20.0	1.8	93.7	76.9
IT.TEA. 2	24.0	234.5	10.0	60.5	20.8	13.8	7.6	19.1	2.9	20.1	24.3	22.0	34.2	46.2	11.1	152.7	9.1	15.2	1.1	43.0	2.9	12.0	18.5	1.8	83.6	80.5
CMA.1	1.8	238.3	16.7	50.8	24.8	14.4	5.7	32.1	2.2	12.7	23.2	36.2	10.0	75.1	15.4	373.5	11.2	10.8	0.9	100.6	2.9	9.6	20.3	1.7	98.5	185.5
CC.1	2.9	130.3	0	53	0.0	9.4	4.7	1.3	2.6	12.0	9.7	12.1	5.1	26.4	16.0	77.5	3.5	13.3	1	27.9	3.8	1.7	16.9	1.8	67.4	87.6
CCG.1	1.9	97.4	0	35.1	0.0	9.8	6.0	15.4	2.1	0.0	9.5	11.5	0.0	6.3	16.0	123.9	0.0	6.8	0.9	11.7	1.1	6.0	12.7	1.7	57.9	7.7

Glauconite is also generally present in this mortar, sometimes in proportions of up to 15%. This is a very common component of tertiary deposits in the Guadalquivir Basin, where it has been associated with two sedimentary levels: an inferior one (Miocene Serravallian), in the transition between Fm. Niebla calcarenite and Blue Marls Units (Fm. of Gibraleón clays), and a superior one (Pliocene), located in the transition between the Fm. Gibraleón clays and Fm. Huelva sand (Galán et al., 1989).

These data suggest that local raw materials were used for the construction of these structures. These raw materials are related to the fluvial dynamics of the Guadalquivir River (fluvial aggregates). A similar trend is also observed in the recently excavated Roman buildings in Patio de Banderas, Real Alcázar, Seville, which have also been analysed (Garofano et al., 2014).

The mortars identified can be divided into four typological groups:

4.1.1. Type 1

Found in the sloping transversal features (IT.SA.1). It is characterised by the presence of rounded, subangular sand particles (40%); sand particle size is predominantly under 2 mm. The carbonate matrix is micro-crystalline and rather compact. It includes a small number of rounded lime nodules (<10%), between 1 mm and 1.5 mm in size. Micaceous and feldspar aggregates often have reaction borders and carbonated halos, which also appear around lime nodules, especially near the surface of the walls. This indicates the advancement of a carbonatation process, which has not run its full course, as demonstrated by the presence of plaques of portlandite inside some pores. The presence of this component helps the carbonatation of mortar because it drives pH towards more alkaline values and neutralises the tendency of acid environments to dissolve calcite (Morse and Arvidson, 2002).

The *caementa* used were large amorphous fragments of calcarenite, rich in fragments of Lamellibranchiate, red algae, benthic foraminifera, Echinoidea, Bryozoa and detritus (quartz and quartzite fragments). This is characteristic of upper Miocene calcarenite in the Guadalquivir valley, which is associated with Fm. Niebla calcarenite and can be found in the vicinity of Italica (Civis et al., 1987).

This mortar type is, in general, homogenous, which indicates a thorough mixing, and it contains few lime nodules. Retraction cracks are absent, which suggests a slow calcination process and reaction to water. In these conditions, lime mixes well with water, assisting the dissolution and carbonatation of portlandite (Boynton, 1980; Yaseen et al., 2013).

4.1.2. Type 2

It is found in the two parallel retaining walls of the main structure, in both the southern (B: IT.SA.8) and eastern sectors (A: IT.SA.3, 5a–f, IT.SA.11 and 12; E: IT.SA.13, 14 and 15) (Fig. 8). Its texture is more heterogeneous, as the proportion of aggregates/binders varies depending on the position of the sample within the wall. In the outermost, whitewashed areas, the proportion of lime can be as high as 60% (Fig. 8a and b). Aggregates are subangular, angular or planar; the latter are relatively oriented (Fig. 8g) and well bound. Brick dust particles (1–1.5 mm) have reaction marks, which indicates a reaction with lime, and carbonated halos.

Lime nodules, in variable proportions (5–25%), are common. Their number decreases towards the outer parts of the wall. They also vary in size, generally between 0.5 and 2 mm, although some exceptionally large examples are over 3 mm in diameter. These large nodules have retraction cracks, which indicate a faster reaction with water or the addition of higher proportions of lime, probably not fully slaked, to the mix. The binding matrix has stains of Fe oxides and secondary crystallisations of sparite calcite, which have an acicular, dogtooth spar and mosaic habit. Small gypsum nodules were detected (including traces of hexahedrite). Remobilised gypsum was also found, needle-shaped and coming out of pores (Fig. 8c). Acicular calcite crystals were found growing out of the pebble's pores (Fig. 8f). This may indicate a significant remobilisation and precipitation of lime-rich fluids into the fabric, which would have affected the *caementa*.

The mortar contains granite *caementa* (IT.SA.9), which are over 10 cm in size (monzogranite, quartz 25%, feldspar 30%, plagioclase 45%, and biotite, which in some cases has turned into chlorite).

4.1.3. Type 3

It is found in the WSA (IT.SA.10, Fig. 9a). Its granulometry is more discontinuous, but homogenous in nature, and it has a high proportion of clayey components. Aggregates under 3 mm in size are predominant, and some are planar in shape (<2 mm). This mortar type has a large number of lime nodules, which are irregular in both shape and size. They are generally around 3 mm, but a significant number is between 1 and 1.5 mm in diameter. Macroporosity is significant (around 30%),

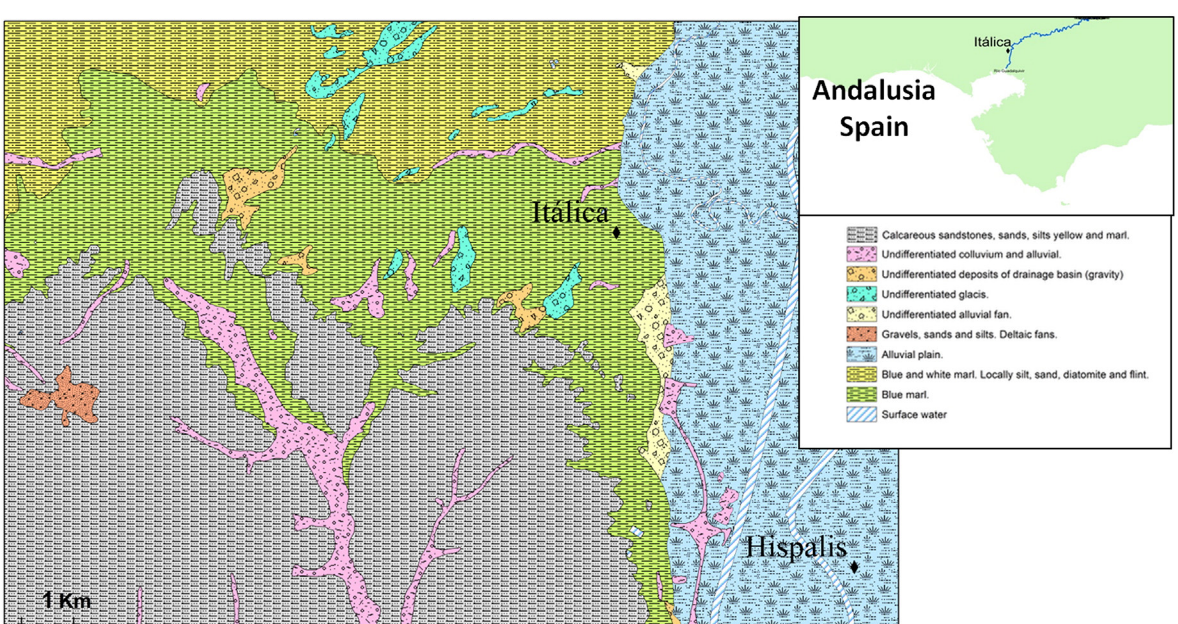

Fig. 6. Italica in its geological context.

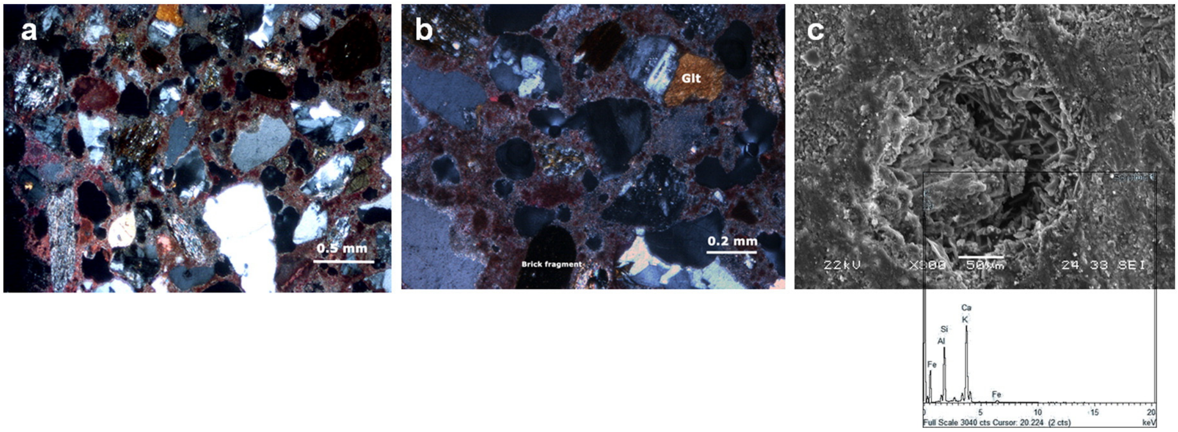

Fig. 7. a. Microphotographs under plane or cross polarised light (XPL) of Type 1 mortar; b. Magnification of a. Porosity observation with a crystal oriented glauconite. c. Secondary electron (SEM-SE) microphotographs of hydrated calcium silicate crystals growing on the surface of a pore.

and recrystallised calcite is frequently found filling pores and fissures. These crystals have a drusy, dogtooth spar and mosaic morphology. This indicates a higher degree of remobilisation of aggregated lime due to its dissolution in water.

4.1.4. Type 4

It is found in the foundation of the theatre stands (IT.TEA.1 and IT.TEA.2, Fig. 9b). It has angular and subangular sand-sized aggregates, and no clayey material. It contains few lime nodules and recrystallised calcite and secondary dolomite. It is similar to Type 1. The main difference is the presence in Type 4 of less of a variety of aggregates (mostly quartzite), including fine gravels. Igneous aggregates in a crystalline calcareous matrix can also be found, which can be related to the smaller proportion of clayey materials. Some similarity with Type 2, also a foundation mortar, can be detected as well.

4.2. Lump lime analysis

The analysis of these particles is revealing concerning the technology used in the preparation of the lime that was added to these fabrics (Elsen, 2006). Several possible reasons for the presence of lump lime in the mortar have been pointed out. One hypothesis suggests that lime was added to mortar, and was slaked in contact with the aggregate. In cases such as this, nodules are rounded in shape (Hughes et al., 1999). A second hypothesis proposes that lime nodules originated in the whitewashed crusts which were caused by prolonged contact with water (Bruni et al., 1997).

Lump lime is present in all this mortar in significant proportions, which indicates that lime was not fully slaked before it was added to the mix. Lump lime appears in different sizes and shapes (from sub-rounded to irregular) (Fig. 10a, b and c), and sometimes it has large retraction cracks. Porosity is common due to dissolution and reprecipitation in the calcite and secondary dolomite. Calcite crystallises in the shape of radial fibrous microsparites (on pore walls) or mosaics (Fig. 10d and e). In other cases, the nodules maintain their original morphology, and thus have a homogeneous micritic appearance.

The proportion, texture and shape of these nodules is different in each of the mortar under analysis: Type 4 is characterised by a small proportion of small sub-rounded shapes, which indicates that lime was added to a more elaborate aggregate, that the mix was more thoroughly kneaded before construction, and that there was a longer process of lime-slakening. Mortars 2 and 3 are characterised by larger, and more frequent lumps of irregular shape, and this suggests a different construction technique: mechanical and chemical interaction between

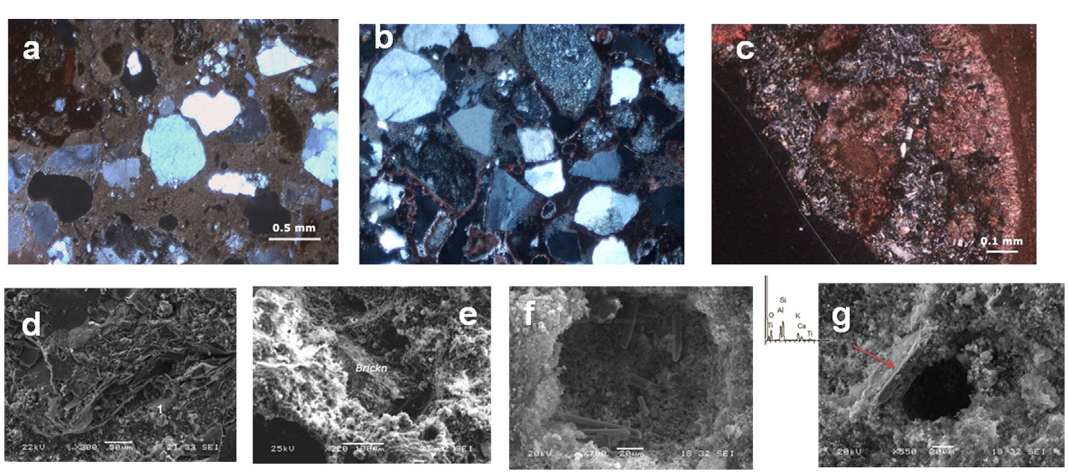

Fig. 8. Microphotographs under plane or cross polarised light (XPL) of Type 2 mortar. a. Mortar with a high proportion of binder; b. mortar with a high proportion of aggregates; c. growth of gypsum crystals with acicular habit inside lump lime; d. reaction marks and formation of tobermorite in a quartz fragment SEM, Se^{-}; e. ceramic fragment inside mortar SEM, Se^{-}; f. development of calcite crystals with acicular habit in a pebble pore. SEM, Se^{-}; g. rounded macropore beside an oriented glauconite crystal. SEM, Se^{-}.

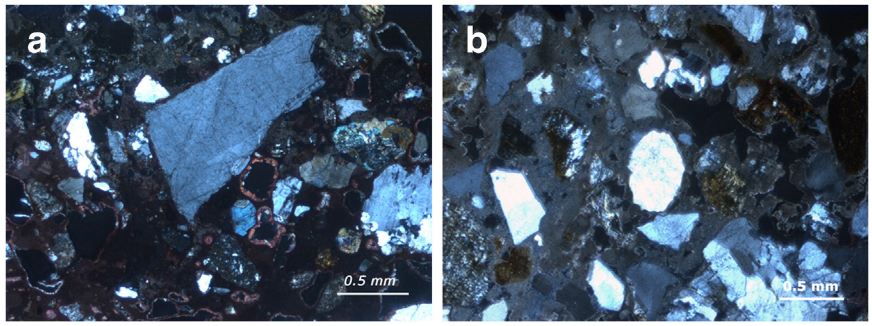

Fig. 9. a. Microphotographs under plane or cross polarised light (XPL) of types 3 and 4 mortar; b. type 4 mortar. XLP.

the aggregates and the lime is more intense. The variability observed between different features that belong to a single construction phase (retaining and transversal walls) cannot be related to different construction techniques, but to the heterogeneity of lime produced by traditional methods, as well as to the mortar-preparation process (for example, the addition of quicklime or powdered lime).

Another interesting aspect was the identification of well-bound fragments of carbonated rock with ghosts of foraminifera and fragments of heterostegina and lamellibranchiata shell. The foraminifera have oxyhydroxide stains and, sometimes, they preserve their original shape. This has been a key factor for identifying the natural rock used in lime production (Elsen, 2006), and also helped us to identify the irregular performance of the lime kilns used, which is a characteristic of traditional lime-firing methods.

The presence of irregular and corroded quartz grains (around 50 μm in size) in the carbonated matrix reveals that these grains were present in the firing process, and are, therefore, detritic components of the rock used in lime production. These elements have allowed for the identification of, at least, the main rock-type used for lime production, but the use of types of rock, and even of different varieties within a single type, should not be disregarded.

This type of rock corresponds to late Tortonian calcareous karts (facies in the outer rim of the Guadalquivir basin), which are composed of fragments of ostreidae, pectinidae, heterostegina, echinoidea, bryozoa, miliolida, pyritised foraminifera and a small proportion of detritic material (quartz grains around 50 μm in size) (Fig. 11a and b). These karts become richer in biomicrite towards the left bank of the Guadalquivir River, which is the most likely extraction area, due to its proximity to Italica and Alcalá del Río (Seville) (IGME, 1975); these rocks are a variation of the Fm. Niebla calcarenite (Civis et al., 1987; Tosquella et al., 1999). Two additional reasons exist to consider this area the most likely source for the stone: the abundance of rocky outcrops near the river bank and the possibility of fluvial transport. Pebbles of this kind of rock have also been found in the interior of walls.

We can, therefore, rule out the use of the late Miocene or early Pliocene calcarenite found in the top layer of Los Alcores, near Carmona (eastern edge of the Guadalquivir basin, Seville). This lithotype is characterised by a high proportion of sand-sized detritic quartz (Espinosa et al., 1996).

The identification of gypsum, a minor component of this mortar, is explained by the traces of this element present in the rocks used for lime production. Guadalquivir basin calcarenite includes variable, and

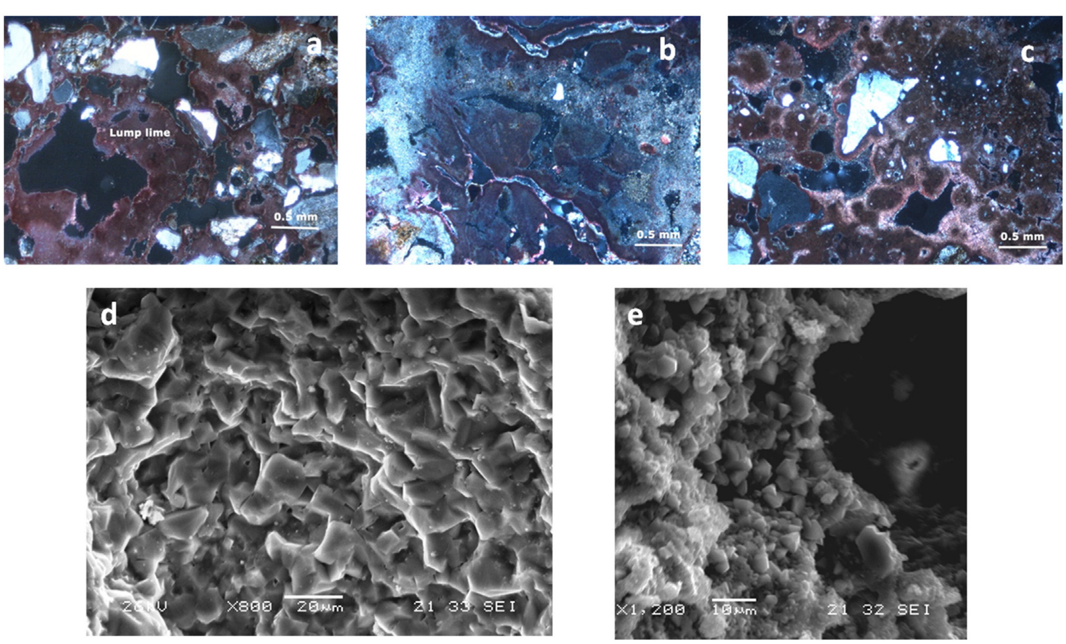

Fig. 10. a. Microphotographs in plane or cross polarised light (XPL) of lump lime with rounded and porous micritic cements observed in Type 4 mortar fissures; b. retraction cracks observed on lump lime in Type 4 mortar. XLP; c. lump lime with quartz grain (50 μm). The carbonation front can be observed in the growth of crystal calcite XLP; d. lime nodule on which the transformation of portlandite plaques into the rhomboid shape of calcite can be appreciated; e. development of calcite crystals in a pore as a result of carbonatation.

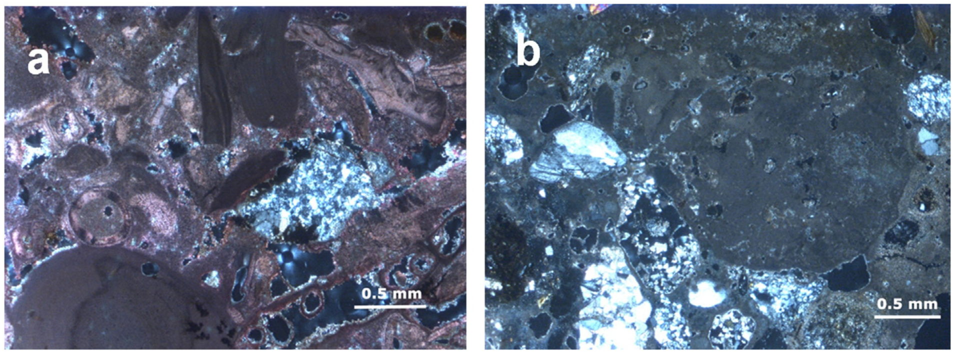

Fig. 11. a. Pebble found in the fabric; the pebble corresponds to the rock used for the production of calcite; gypsum may be observed in the rock pores; b. fragment of semicalcined rock.

sometimes significant, proportions of gypsum. In the mortar, gypsum appears in the shape of overfired nodules within the binder or as a result of recrystallisation processes in pores and cracks. These nodules are easily visible in Type 3 mortar (MOP and FRX). This may indicate the use of a variety of calcarenite with a higher proportion of gypsum and, therefore, a different rock source. This is interesting since physical and stratigraphic relationships suggest that this mortar was used in a different construction project.

Trace element analysis is also of interest in this regard. The geochemical composition of the nodules and the whitewashed areas was compared with data from samples CC.1 and CCG.1 (late Miocene calcarenite, used as *caementa* and found in the natural state, respectively). Trace elements in these samples vary, especially in the rock samples — something which may be explained by the variability of the detritic content of calcarenite. Notably, there is little or no As, Co, Pb or Ta in rock samples, and a low Ba content can be noted. The whitewash, on the other hand, had a higher content of silica, alumina, Fe oxides and trace elements, due to the presence of silt- and sand-sized aggregates.

4.3. Analysis of the calcareous crusts

A number of calcareous crusts were identified in well-sheltered areas of the frontal faces of the main walls. As demonstrated by their examination with the petrographic microscope, these crusts were left as a sort of lime-rich cast when the wooden shutters mineralised and disappeared due to the absorption of lime and the saturation of their porous system, a process which was probably also assisted by pressure. It is thus clear that wooden shutters were not removed after the mix hardened.

The study of the imprints left by the shutters is of interest. Fig. 12 (a: observation through optic microscope a: SEM b, c and d) illustrates the imprint of the anatomical texture of a conifer: the tracheids (Fig. 12a) are filled with rhomboid sparitic calcite crystals (also observed by SEM, Fig. 12b), which proliferate in conditions of high concentrations of portlandite (Cizer et al., 2008).

The remobilisation of lime during the construction process indicates the plastic nature of the binder. This suggests that the lime was slaked

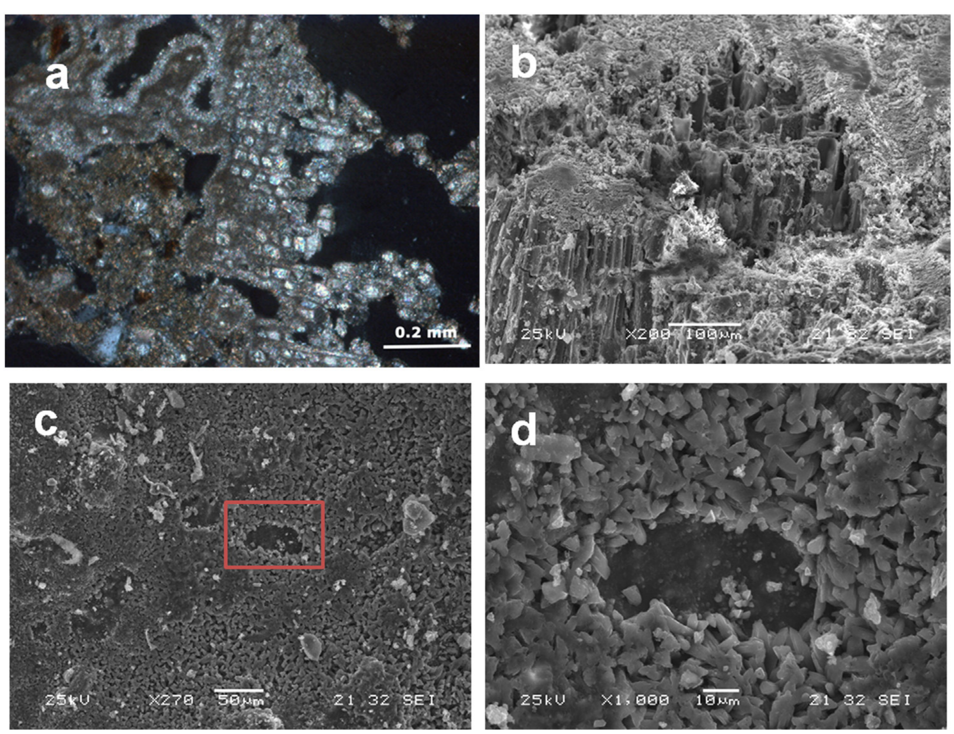

Fig. 12. a. Recrystallisation of calcite crystals in the original tracheid conducts (transversal section of a piece of coniferous timber) XLP; b fossilised timber, tangential section SEM, Se⁻; SEM detail of a tracheid with calcite crystals with tabular habit Se⁻; c. development of a thin non-permeable carbonate layer over the tracheid (tangential section) SEM Se⁻; d. detail of a xylem conduct.

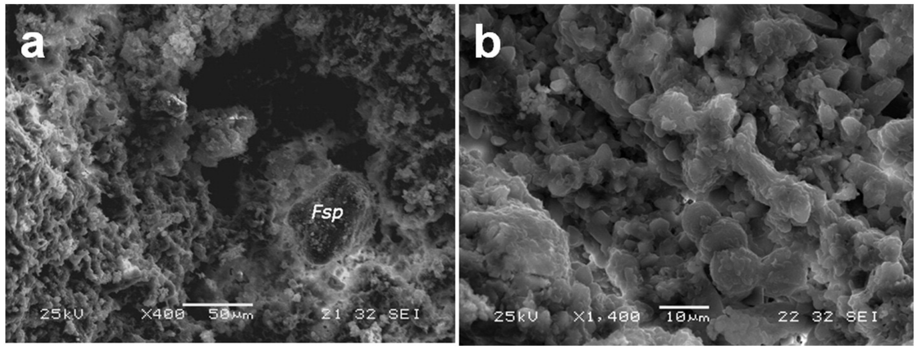

Fig. 13. a. Feldspar aggregate on the surface layers; b. interfacial transition zone between aggregate and binder.

before it was added to the walls, but the proportion of lime nodules indicates that slaking was not completed. It cannot be disregarded, however, that the penetration of lime into the pores was facilitated by the remobilisation of lime-rich fluids.

These fluids deposited a thin film of calcium carbonate over the surface of the mineralised wooden shutters, forming a network of pores with a maximum size of 5 μm (observed by SEM). Under the crusts, a thin layer of lime whitewash developed (Fig. 12c and d) due to the movement of fine particles towards the exterior of the walls. This formed a transitional layer between the mortar and the timber, which suggests that the mortar was probably pressed while it hardened. These layers contain very fine aggregates (100–50 μm) and a lime-rich matrix. The ITZ (Interfacial Transition Zone) is very compact and rich in calcite crystals, which are well-bound to the surface (Fig. 13).

4.4. Physical properties of the mortar

The good state of preservation of the mortar allowed for the analysis of their physical properties, which provided relevant information concerning their quality and preservation. The results are as follows.

4.4.1. Grain size analysis

Previous studies suggest that the main factor concerning the quality of the mortar mix is the maximum size and granulometry of aggregates (Borges et al., 2010). They are crucial for the mortar's load capacity and mechanical resistance, and therefore its cohesion and hardness (Arizzi and Cultrone, 2013). The function of aggregates is to fill the gaps left by larger particles. A good distribution of aggregates reduces retraction and has an effect on porosity (Barbero Barbera, 2012).

Granulometric curves are illustrated in Fig. 14. They have been divided into groups, as described above, with reference to Fuller–Thompson's curve. Fractions over 10 mm have been left out of the curve, as well as inclusions, ceramic or lithic, over 10 cm in size, which are common in these mortar. In most samples, the proportion of aggregates is over 10%.

Types 2 and 4 contain coarse sand (1 to 2 mm) and 10% of each is made up of fine gravels. Differences in granulometry are due to the fine sand content, which is lower in Type 4 and some samples in the more heterogeneous Type 2 found towards the outer faces of the walls. Cu (see Table 5) values, which oscillate between 7 and 12, indicate that sands were well-sorted. Mortar Type 1 also contains well-sorted sands, without fine gravel and with a Cu value of 10.

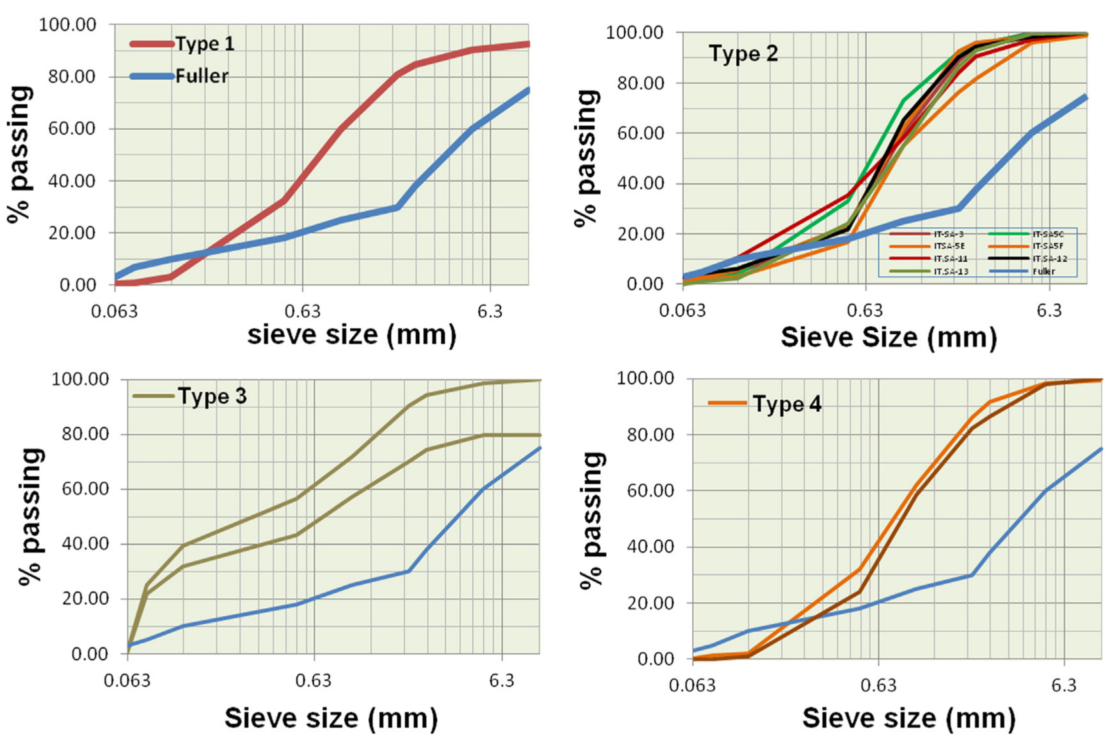

Fig. 14. Particle-size distribution of aggregates.

The most characteristic samples in terms of granulometry correspond to Type 3, which are rich in fine sand (>20%) and a lower proportion of medium sands. Cu values are under 5, and the value for Cc is 9, which is far from the ideal values (1–3). This suggests that poorly sorted, discontinuous materials, which were also rich in silty and clayey contents, were used.

4.4.2. Density

The density of mortar depends on the nature and proportion of aggregates, as well as the way they were added (Barbero Barbera, 2012). Bulk density in all of the mortar analysed was very similar, with values around 1.6 g/cm^3. Real density values, however, vary significantly, depending on the granulometry of the aggregates. Type 1 has a density of 3.93 g/cm^3, as a result of its content in well-sorted sand. Type 2 has a density of 2.7 g/cm^3 and, finally, Type 3, has a density of 2.5 g/cm^3; this low density is due to the high proportion of fine sand.

The so-called 'calcareous crusts' (observed in Type 2) are the less dense of the material sample (2.0 g/cm^3). As previously noted, these formed out of the macro-porous mineralised timber.

4.4.3. Porosity and spectrum of porosity

Porosity and pore-size distribution are the most influential variables concerning the physical properties of lime mortar, as they are a key factor in the progressive carbonatation and, therefore, hardening of the mortar, while they also have a direct impact on hydro-dynamics, which is the most important degradation factor (Arandigoyen et al., 2006). Pore size and distribution are defined during the preparation process: the water content of the mix, the granulometry of the aggregates and the nature of the lime are significant variables. The more water that goes into the mix, the higher the porosity (Arandigoyen et al., 2005).

Lime type is particularly important concerning microporosity: if pores are small, for example with traditional lime, microporosity will

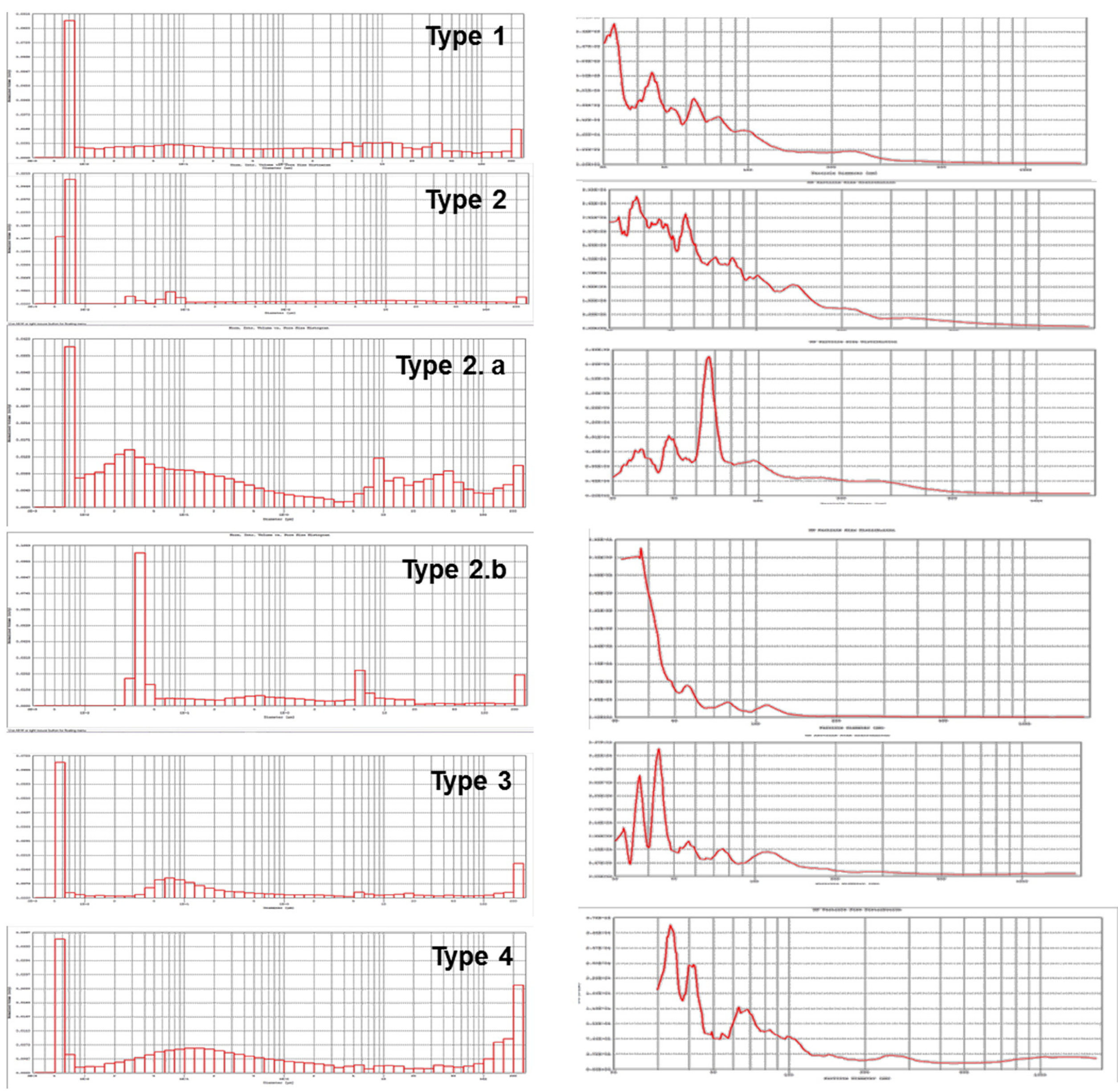

Fig. 15. Spectrum of porosity measured by mercury intrusion porosimetry (MIP).

increase due to a more intense degree of carbonatation (Cazalla et al., 2000). In addition, the volume of intergrain gaps, the size ranges and specific surfaces are also determined by granulometry and by the nature of the aggregates, both of which have a strong bearing on the ITZ between the sands and gravels and the binder (Arizzi and Cultrone, 2012).

Porosity to water values are very similar in all of the mortar under analysis (pores in the 0.1 μm-10 mm range are quantified), around 32%, with a significant presence of macropores (: >60 μm, Choquette and Pray, 1970). This proportion increases in calcareous crusts (nearly 60%). Type 3 mortar is the most porous, with values around 40%, which is in agreement with their density and granulometry. Rounded pores, which are very common in this mortar, are related to the liberation of water bubbles (Cazalla et al., 2000).

Porosity and specific surfaces of the samples, which have been analysed by mercury intrusion porosimetry (range 0.001–0.1 μm), are shown in Fig. 15 and Table 6.

In general, this mortar is lacking in pores under 0.002 μm (gel pores), which indicates a low tendency to retain water by capillarity (Arandigoyen and Álvarez Galindo, 2006). Microporosity in Type 2 mortar increases towards the surface of the wall. The interior samples have a dominant pore size range of 0.003–0.006 μm, and somewhat fewer pores in the 0.03–0.01 μm range. Type 3 mortar has the same tendency, with two dominant pore ranges of 0.006 μm and 0.03–0.02 μm (although this range is significantly larger). This suggests that all of these walls were built using the same technique. The most significant difference between types 2 and 3 affects microporosity: Type 2 mortar has a wider range (30–100 μm) than Type 3 (40–50 μm), due to the latter's granulometric features (higher content of fine particles).

Mortar Type 1 has a wider pore size range, between 30 and 90 μm, and a peak of micropores 0.007 μm in size. This porosity spectrum corresponds with that found in Type 4. The main difference is the presence of micropores (0.03 and 0.5 μm) and a higher content of pores within the 30–100 μm range in the former, which may be explained by its higher fine gravel content.

Whitewash (Fig. 15, Type 2.a) and calcareous crusts (Fig. 15, Type 2.b) are characterised by a wide microporosity range, between 0.2 and 0.006. Pores 0.006 μm are predominant, and pores under 0.02 μm in size are absent. There is a significant presence of pores between 0.03 and 0.05 μm, as well as around 40 μm in size (also observed by SEM).

Surface data indicate significant differences between samples in terms of microporosity: mortar types 1 and 4, as well as the most superficial mortar (calcareous crusts and whitewash) yield the lowest values. In conclusion, the mortar types that are richest in lime are also those that have a wider porosity range and lower specific surface values. This is also in accordance with Arandigoyen et al. (2005) concerning the effects of carbonation on lime mortar: a lower specific surface results from lower porosity (<0.03 μm), since, in general, the addition of lime to the walls increases the microporosity of these materials (Cazalla et al., 2000).

In the whitewash layers, porosity is higher. It must be taken into consideration that, the smaller the pores, the more likely it is that water condensation within the walls will take place, and permeability will thus drop. Ideally, therefore, pores should be of a size that prevents internal water condensation while they should also act as an impermeable barrier. This characteristic explains the formation of carbonated layers on the surface.

Finally, the generalised presence of micropores (between 0.006 and 0.008 μm in size) in all this mortar can be related to the sand used (it is absent from the whitewash layers and the calcareous crusts).

4.4.4. Hydraulic properties

The water absorption and desorption curves corresponding to mortar types 1 and 2 are shown in Fig. 16. Given the size of sample required for this sort of test, we have not been able to determine the hydraulic properties of the other types of mortar. The curves indicate fast saturation and drying, which reveals that this mortar is essentially macroporous and interconnected, and this fits well with the porosity and water data. These curves define several stages concerning water absorption. Initially, water is absorbed rapidly, followed by a stage in which water absorption progressively slows down until it becomes stable. This indicates a broad porosity range and a high percentage of effective porosity. In Type 2, the second absorption stage is slower, which suggests a smaller proportion of pores within the 0.001–100 μm range, or a more tortuous porosity. This tendency is also reflected in the desorption curve, which indicates that Type 2 mortar does not retain water for as long as Type 1.

4.4.5. Mechanical properties (compressive strength)

This initial stage of research has determined only the compressive strength of Type 1 mortar, as it has not been possible to take large enough samples from the other types to carry out this test. The value for Type 1 is 76 MPa, which indicates that, in accordance with their physical properties and their state of preservation, this mortar is highly resistant. The application of the phenolphthalein test has revealed that this mortar type has undergone a near-total carbonatation process. The high values yielded by the mechanical resistance test seem to be due to the significant presence of clay nodules in the samples. At all events, this is but a preliminary test on the mechanical resistance of Roman mortars, which is of considerable interest due to the paucity of similar studies. The data here provided are, therefore, merely indicative and must not be regarded as definitive.

5. Discussion and finishing remarks

The analysis of the mortar used in the important building programme undergone by Italica during the reign of Hadrian has provided important evidence with regard to the construction techniques used and has indicated the generalised used of local raw materials.

In general, these analyses have been revealing concerning the techniques used in the preparation of this mortar, and thus they can be used as references for future comparative studies, either involving other buildings in the city or other coeval constructions

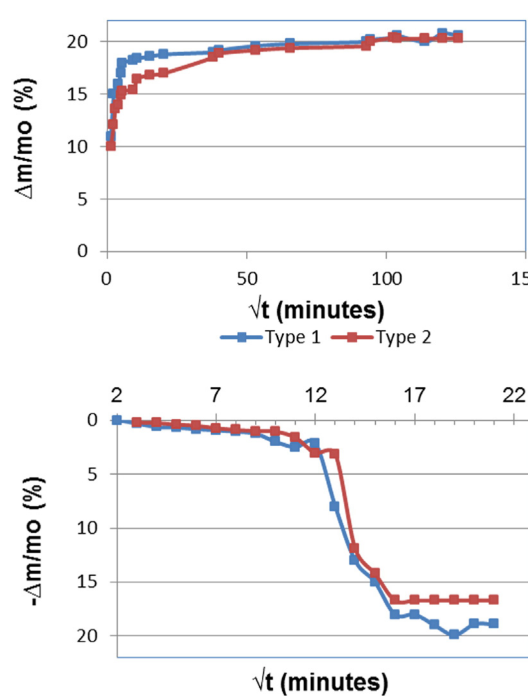

Fig. 16. Water absorption and desorption curves in types 1 and 2.

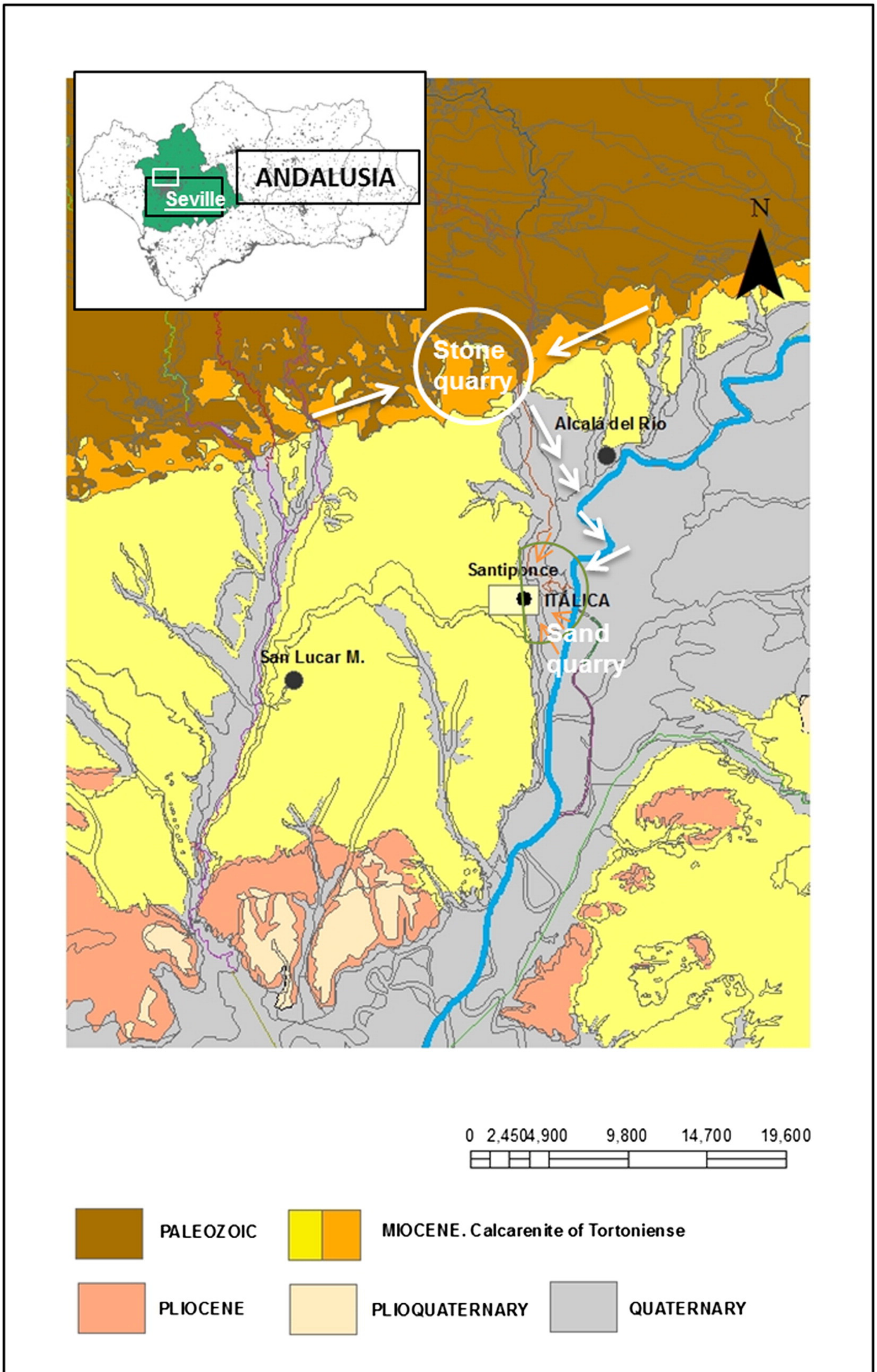

Fig. 17. Probable source areas of raw materials.

elsewhere in the Roman Empire. Some comparisons with other nearby buildings have already been presented, and this may be the most useful dimension of this strand of research.

The analytical programme was tailored in order to meet the research objectives: to identify the source areas of raw materials based on mineralogical and chemical characterisation, to determine the construction techniques used and, finally, to reveal the physical characteristics of this mortar and thus to establish a series of technological parameters for public construction in Italica during the reign of Hadrian.

5.1. Raw material source areas

– The materials used were essentially local in origin. No foreign materials have been identified (Fig. 17).
– The mortar included alluvial sands from the Guadalquivir River, which are rich in quartz, feldspars, igneous rock fragments, glauconite and blue marl. Concerning additives, we have observed the presence of ceramic fragments as an additive (in a proportion of approximately 5%), probably architectural in nature, such as bricks, which give these mortars some degree of hydraulicity. The mortar contains significant proportions of blue marl added as *caementa*, the purpose of which was to improve the mortar's mechanical, rather than hydraulic, qualities.
– The lime came from the calcarenite outcrops localised on the southwest bank of the Guadalquivir River, which are associated with the Niebla Calcarenite. These rocks were most likely sourced from the vicinity of the modern-day town of Alcalá del Río. Lime appears in this mortar in different proportions, but it is always produced from the same kind of rock (which, in turn, has different proportions of lime in its natural state).
– Coniferous timber was used for the shuttering of the mortar. This timber was probably shipped up the river (from Huelva) or, more likely, floated down (from Cazorla) forming rafts.

5.2. Technical processes

– Aggregates are generally sand-sized and well-sorted: some variations exist concerning the proportion of fine gravels in the mortar used in foundations, which indicates that the composition varied based on the structural function of each architectural features (for example, braces and sloping platforms). The materials used for the construction of the WSA were selected with less care. The proportion of fine particles (silts and clays) is high, which probably indicates that some of the materials used were obtained in the immediate vicinity of the construction. It is also possible that similar materials were used in the other mortar, but that they were more carefully selected or sieved before use.
– The lime added to this mortar was not fully slaked, as indicated by the high presence of lime nodules and the heterogeneity of the slaking process. In foundations and retaining walls, it is likely that semi-hydrated quicklime was added. In any case, this does not seem to have affected the good quality of the end result.
– The proportion of lime is around 1:4. The proportions suggested by Vitruvius for this kind of mortar are 1 part lime, 3 parts quarry sand and 2 parts river sand. In the present day, the recommended proportion is 1 part lime and 4 parts sand, for foundations and masonry walls (Sánchez-Moral et al., 2004).
– Some superficial layers have been preserved in the retaining walls, and these have been very revealing concerning the construction process. The deposition of a very thin layer of whitewash under the remains of mineralised timber, on the vertical surfaces of the walls, is indicative of the 'expulsion' of fine particles towards the exterior by artificial pressure, with the timber acting as a barrier. This process also resulted in the impregnation of the fabric and the pores by a lime-rich fluid, which has left an imprint of the anatomic characteristics of the timber (mineralisation process) and the formation of a thin, carbonated film on its surface. Lime-content variations are also visible depending on the position of the samples within the wall (the lime content is higher in samples that are close to the wall surface). Microporosity is higher in internal mortar.

5.3. Physical properties

The determination of the variables on which we have focused is often limited in historical constructions by the size of the samples that are necessary for the completion of normalised tests, but is nonetheless of enormous interest for the determination of the structural function of architectural features and the construction techniques used. In this case, it is desirable that similar procedures are applied to samples collected from other buildings in the city and other nearby settlements, as only in this way can we determine whether the techniques used in these buildings were widespread or not. It is likely that this sort of project, which would have been both large and expensive, was executed by highly specialised builders who were well versed in the characteristics of these fabrics.

The physical properties of this mortar, such as granulometry, the composition of aggregates, and the nature of the lime (preparation and self-healing), are closely connected with the nature and selection of the raw materials (Cazalla et al., 2000; Arizzi and Cultrone, 2013) and the additives. Additives have not been analysed in this work, but will be the topic of future works. Carbonation of the mortar is nearly complete, and is responsible for their good quality. This was achieved through the use of well-sorted materials, which is a crucial variable for the density, porosity and mechanical resistance of mortar, as clearly evidenced by our Type 1. A discontinuous granulometry and a high content of fine particles decreases density and increases porosity, as demonstrated by the WSA.

The fact that lime was only partially slaked before it was used in the retaining walls and the WSA is attested by the high number of lime nodules in the mortar. It is even likely that it was added as quicklime, depending on the needs of the construction process. This study has demonstrated that the addition of lime in these conditions had a significant impact on the remobilisation and secondary precipitation of carbonate in pores and micro-cracks.

The proportion of gypsum contained within the lime also seems to have no effects on the good structural qualities of the mortar, judging by the results of the tests carried out on Type 1 mortar (the lime within this type contained gypsum).

The walls have a thin layer of calcium carbonate that acts as a protective film against external weathering agents. This is not only present below the timber, but also on top of it. Microporosity in this whitewash would have increased the wall's non-permeability while favouring transpiration and thus avoiding interior water condensation.

5.4. Structural features

– The analysis of the properties of the mortar reveals that there is considerable variation between different features, which also fits well with the stratigraphic observations. All the evidence thus suggests the different constructive nature of the WSA.
– According to the data, the Hadrianic structure is homogenous in terms of quality and composition of the mortar, even if some differences

Table 5
Cu and Cc values.

Sample	Cu	Cc	Type
IT.SA.1 (T1)	10	1.6	Well graded
IT.SA.3 (T2)	8.33	3.25	Sorted
IT.SA.5c (T2)	10	1.06	Well graded
IT.SA.5e (T2)	12.5	2.1	Well graded
IT.SA.5f (T2)	6.7	1	Well graded
IT.SA.10 (T3)	4	9	Very uniform and discontinuous
IT.SA.11 (T2)	10	0.9	Well graded
IT.SA.12 (T2)	6.7	1	Well graded
IT.SA.13 (T2)	13	1.38	Well graded
IT.SA.15 (T2)	10	1	Well graded
IT.TEA.1 (T4)	10	1.06	Well graded
IT.TEA.2 (T4)	5.6	1.81	Well graded

Table 6
Surface area values.

Sample	SA [m^2/g]
IT.SA.1 (Type 1)	63.8002
IT.SA.3 (Type 2)	31.73
IT.SA.4 (Type 2, C)	44.42
IT.SA.7 (Type 2, P)	16.78
IT.SA.8 (Type 4)	52.13
IT.SA.11 (Type 2)	302.36
IT.SA.13 (Type 2)	239.99
IT.SA.15 (Type 3)	143.38
IT.TEA.1 (Type 4)	31.73

P: plastering, C: crusts.

exist between features with different structural functions, for example, vertical walls and perpendicular braces and oblique walls. The latter are not only different in terms of structural function, but also construction technique. In fact, one of the most relevant conclusions of this study is that most of this mortar was subject to pressure while hardening, although evidence of this is lacking in the case of Type 1 mortar.

– Despite the aforementioned homogeneity, differences have been detected in the use of *caementa*, which may be due to the temporary availability of different materials or even construction waste from other projects. In this regard, the presence of some amorphous granite fragments, which were almost absent elsewhere in Italica but common in nearby regions (for example, around modern-day Gerena), may be highlighted.
– The data suggest a well-planned project: materials were selected and depurated carefully and the preparation of the fabrics was expertly carried out.
– The homogeneity of mortar and the dimensions of sands and *caementa* suggest that no vertical hierarchy of materials existed, which confirms that all of the preserved features acted as foundations. At any rate, this homogeneity speaks of a well-organised project in terms of raw-material supply and distribution within the building site.
– The dimensions of the project are also made clear by the level of expenditure incurred. Materials were highly depurated, and many wooden shutters – made with large and costly coniferous timber boards – were lost in the process of construction.
– The resulting fabrics are characterised by their resistance and non-permeability. It is likely that both were intentional features, not only because of the monumental nature of the work and the desire to make it last – it was to support a sacred public space – but also of its position on an exposed hilltop.

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