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# New Method for Historic Rammed-earth Wall Characterization: The Almohade Ramparts of Malaga and Seville

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ORIGINAL RESEARCH OR TREATMENT PAPER

# New Method for Historic Rammed-earth Wall Characterization: The Almohade Ramparts of Malaga and Seville

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**ABSTRACT**
The goal of this research is to propose a new method of characterizing rammed-earth walls. Based on their historic building materials properties, five broad test groups were established for the characterization: chemical and mineralogical composition, physical properties, mechanical properties, particle size distribution, and dating. These determinations can, in turn, be grouped into two different types: instrumental techniques such as XRF, XRD, and SEM-EDX, as well as adaptations of standard methods (mainly UNE-EN standards) for application to these materials. As case studies where the proposed method is applied, we present our research on the rammed-earth walls in the ramparts of Seville and Malaga (Spain), clearly showing the method's capacity for comparing and differentiating different rammed-earth walls.

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Rammed-earth; methodology; characterization

## Introduction

Rammed-earth walls are termed *tapias* in Spanish, which is a transcription of the Bereber term *tabiya*, which became *toub* in other parts of Africa. In French, this technique is called *pisé (de terre)* or *terre pisé*, and in German it is *stampleflehmbau*. It is defined as a masonry work, basically modular, made by placing a formwork (called a *tapial*) and filling it with dirt and/or other components, then tamping it down in batches (Ontiveros Ortega, Valverde Espinosa, and Sebastián Pardo 2006). The earth is poured loose in layers about 10–15 cm thick into a timber or metal formwork, which is then rammed with a rammer (manual or pneumatic). After compaction, the thickness of each layer is typically 6–10 cm. Other binders can also be added such as cement or hydraulic or calcium lime, which is often called 'stabilized rammed earth' (SRE). The main advantage of stabilization is the increase in durability and mechanical performance. However, stabilization increases the construction cost and environmental impact. The procedure is repeated until the completion of the wall. A detailed presentation of rammed earth construction can be found in (Walker et al. 2005). To build rammed-earth walls, a formwork is used made of two vertical planks parallel to each other, with a space between them and joined by horizontal timbers (Villanueva 1827).

Construction using rammed earth that includes the use of locally available soils stabilized with binders such as lime dates back many centuries. Rammed-earth structures including walls have been built in numerous countries (Earth Materials Guidelines 1996).

Depending on the construction system, there are many varieties of rammed-earth walls based on the techniques and materials available at different sites. There are two main groups: (1) Monolithic rammed-earth walls (royal rammed-earth wall), in which the wall is a homogeneous mass of equal strength, basically comprising earth and lime. (2) Mixed rammed-earth walls (Valencian, stone and brick), in which specific points in the wall bearing the main loads are reinforced with brick and mortar. For instance, brick-reinforced rammed earth (Valencian) contains ceramic bricks and a lime mortar poured in the outer part of the box next to the formwork in a process very similar to lime-crust wall construction (*calicastrado*) (Canivell 2011).

Rammed earth is a focus of scientific research for two main reasons: first, in the context of sustainable building, the modern interest in earth as a building material is largely derived from its low embodied energy, both for unstabilized rammed earth (Morel et al. 2001) and stabilized rammed earth (Reddy and Kumar 2010). Second, the heritage of rammed-earth buildings in Europe and the world is still significant (Bui et al. 2009) and maintaining this heritage requires scientific knowledge to assess appropriate renovations. Several studies have recently been conducted to study certain characteristics of the rammed earth: durability and sensitivity to water, thermal properties, living comfort, and mechanical compressive strength (Bui et al. 2014).

Specialists coming across this material during restoration and conservation work are faced with gaps in their knowledge on appropriate interventions

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(conditioned by the composition and building system). It is vital to carry out preliminary studies and tests to determine the wall's characteristics and behaviour in order to approach the intervention with the best chance of success in each specific case (Matoses Ortells and Hidalgo Mora 2013).

Therefore, a correct interpretation of a characterization using instrumental techniques or current standard methods should aim to provide researchers and technicians other than analysts (historians, archaeologists, restorers, architects, etc.) with a better understanding of the material, the building elements, and their evolution over time.

Research studies on experimental techniques for characterizing rammed-earth walls provide a partial or very specific approach compared to methods applied to other materials such as stone, brick, or mortar (Cope 1984; Houben and Guilland 1989; Torres López, Sebastián, and Rodríguez 1996; Barbeta Solá 2002; Ontiveros Ortega, Valverde Espinosa, and Sebastián Pardo 2006, 2008; Sebastián and Cultrone 2010; Barrios et al. 2012).

Most of the methods in these works are based on determining the parameters related to soil mechanics, such as plasticity via the Atterberg limits, optimal density via the Proctor test (Hall and Djerbib 2004), and clay physical–chemical properties (chemical composition determined by X-ray fluorescence and mineralogy by XRD), which in many cases is insufficient to completely characterize rammed earth (Gurriarán and Snacel 2014).

## Objective

The objective of this work is to propose a new methodology to characterize historical rammed-earth walls in order to broaden knowledge of this material, systematize previous studies, and to serve as a reference for other investigators. Five broad groups are established for analysis and determinations: chemical and mineralogical composition, physical and hydric properties, mechanical properties, particle size distribution, and dating.

The methodology was tested on samples from Almohade ramparts in Seville (Ramírez Reina and Vargas Jiménez 1995) and Malaga to verify the data collected in the different tests, their comparative and differentiating capacity, and its usefulness prior to restoration.

## Procedure for characterizing historical rammed-earth walls

The advised plan for characterizing this type of material (composition, properties, and alteration processes) is based on that proposed by Martín Pérez (1990) for historic mortars.

### *Sampling*

The sampling criteria for historic mortars are broadly extrapolable to rammed earth. A sampling plan must take into account the following points:

(a) Maximum representativity. Rammed-earth walls are extremely variable in composition due to multiple factors: inaccurate manual doses, heterogeneity of components, imperfect batching, and non-uniform manual application methods. Consequently, efforts should always be made to ensure the samples collected are representative of the rammed-earth wall under study.

(b) Number of samples. To validate the results with respect to the rest of the elements in a building/edifice, the uniformity of the rammed-earth wall must be assessed. Consequently, at least two samples should be taken from different sites for each of the types determined by an initial visual inspection. Once analysed, these samples should produce results falling within a suitable range keeping in mind the heterogeneity these materials can present.

(c) Condition of samples. The condition of the samples must be taken into account in establishing the specific methodology and the analyses that are feasible. Samples may be compact or fragmented (crumbled). In compact samples, both the chemical and mineralogical composition and structural properties (physical–mechanical) can be studied; however, in fragmented samples, only compositional analyses can be performed.

(d) Extraction can be manual (with chisel and hammer) or semi-manual using a pneumatic drill or a rock drill with diamond cups of varying diameter.

(e) Sample amount. Sample size varies depending on various factors such as limiting damage during extraction, homogeneity of the wall, and the amount of sample required for each test or determination. Generally, it ranges from at least 500 grams to several kilograms. Subsequent sample crushing is very important to ensure representativity and homogeneity.

(f) Depth of sampling. The depth at which a sample is collected in a wall is extremely important. The deeper it is, the greater the possibility the sample is original and untouched by substitutions, repairs, or alterations. In contrast, when the sample is collected near the surface, it is more likely to have been partially substituted or repaired, in addition to being more weathered by atmospheric agents. It is common to find patinas, crusts, efflorescences and more on the surface. The collection site may also reveal different means of execution, differences in dosing, or uneven binder distribution (e.g. lime-crust walls – calicastrado).

(g) Sample humidity. Moisture is the main cause or concause of decay of rammed – earth walls, so knowledge of its content can lead to very important decisions concerning the restoration and conservation strategy to be adopted. A wide range of measurement techniques is presently applied for detecting its presence in buildings materials, but the calcium carbide and gravimetric methods are the most reliable for a quantitative measurement of moisture content, by suitable sampling (Sandrolini and Franzoni 2006). Determining humidity at different depths of the wall involves drilling, so the use of low-speed drilling for sampling at the selected depth is recommended in order to avoid samples heating and moisture loss by evaporation.

(h) Sample identification. Once the samples have been collected, the precise location must be noted (photographs and drawings), and they must be identified by a suitable system allowing rapid, clear identification to prevent confusion.

## Chemical analysis

Determining the chemical composition requires an analysis of the major and minor elements, which in rammed-earth walls are usually silica, aluminium, iron, titanium, calcium, magnesium, sodium, potassium, and sulphur. They are expressed as oxides in percent by weight as well as by the determination of weight loss on calcination at 900°C (LOI). These parameters can be complemented with the determination of trace elements (Cl, Pb, Zn, Cu, Ni, Co, Mn, Ba, Cd, Sr, Li, etc.) depending on the specific characteristics of the object of study.

Occasionally, soluble salts in the wall are also analysed ($Cl^-$, $SO_4^=$, $NO_3^-$, $Ca^{+2}$, $Mg^{+2}$, $Na^+$, $K^+$, $Fe^{+3}$, etc.) as they can interfere in alteration processes. This type of analysis may also be performed on materials to be introduced during a restoration since, if present in high concentrations, they could be incompatible with the original wall materials.

The analytical techniques that can be used to determine chemical composition are quite varied, ranging from classic methods consisting of gravimetry and volumetric analyses to those using instrumental techniques more commonly applied at present such as X-ray fluorescence (XRF), X-ray microfluorescence (μ-XRF), plasma spectrometry (ICP), and absorption spectrophotometry (atomic, ultraviolet, infrared).

Carbonate determination (expressed as %$CaCO_3$) through the Bernard calcimeter (UNE standard 103200-93) is valid for approximating the original lime content ($Ca(OH)_2$) in walls made with it since over time the lime carbonates and becomes calcium carbonate. However, it must be recalled that both the earth and the aggregates used in its manufacture may naturally contain carbonate fractions. Therefore, the entire carbonate content is not always attributable to the addition of lime.

Determining the sulphate content (expressed as SO3) according to the UNE-EN 1744-1:2010 standard is also proposed as it evaluates the presence of gypsum ($CaSO_4{\cdot}2H_2O$) in the wall. The gypsum may have been intentionally added as a binder or be present as an impurity in the raw materials. This parameter can also offer information on the presence of sulphate salts ($SO_4^=$).

## Mineralogical analysis

The aim of studying the mineral composition is to gather information on the distinct crystalline mineral phases in the wall. The sample mineralogy is dependent on the raw materials, on the reactions produced between them, and on the transformations occurring when they enter into contact with other materials in the environment and that can produce new products by the alteration of the existing ones. The researcher would be advised to know the mineralogy in the soil near the site where the wall has been erected since it can aid in more easily identifying the mineral composition of the samples and deducing the origin of the materials used.

X-ray powder diffraction (XRD) has been used for determining bulk mineralogy. To identify the minerals in the clay fraction, the <2 micron fraction must be studied using the oriented aggregate technique. The sample is solvated with ethylenglycol (EG) and dimethyl sulfoxide (DMSO) and heated to 400–550°C as routine treatments to identify clay minerals (Brown 1961).

By XRD it is also possible to quantify clay minerals content. If they are very abundant in the rammed-earths it is possible to obtain diffraction patterns of sufficient resolution for Rietveld analysis. However, if the concentration of clay minerals is lower, bulk quantitative analyses could be carried out based on the Schultz (1964) method, after correcting intensities for the automatic slit and phase abundances could be semi-quantitatively estimated according to mineral intensity factors proposed by Martín Pozas (Martín Vivaldi, Rodriguez Gallego, and Martín Pozas 1968; Martín Pozas, Rodriguez Gallego, and Martín Vivaldi 1969). This methodology is similar to that generalized by Chung (1974) later.

The mineralogical analysis (depending on sample cohesiveness) can be completed by studying thin sections by polarizing microscopy (PM) and image analysis, which allows the principal components of the rammed-earth wall (binder and aggregate) and the mineralogical constituents of the aggregate to be determined in relative terms.

### Textural analysis

The study of the texture of the wall components is of interest to determine the distribution of aggregate grains, their shape and alteration, as well as the state of the aggregate-binder interfaces. The textural analysis of the binder reveals information about its crystallization, the presence of lime nodules, charcoal remnants, ashes, and so on (Figure 2). It is also useful for observing the presence of pores and fissures and their geometry and distribution.

The binocular microscope is useful for this study, using magnification intervals of 20–60X. Scanning electron microscopy (SEM) and polarizing microscopy are also complementary techniques for textural study.

### Determination of physical properties

The physical properties included in a routine rammed-earth wall characterization are real density, apparent density, and water-accessible porosity, which all provide information on the material's structure.

Real density is part of the material's intrinsic properties and depends in turn on the real density of its components. Apparent density depends on various factors such as water dosing, particle size distribution of the aggregate, and the method of execution.

Finally, the water-accessible porosity provides information on the wall's conservation status, the amount of water used in its manufacture, and the structure's compactness. It also exerts considerable influence on other physico-mechanical properties such as mechanical strength, hardness, permeability, and so on.

The techniques for determining these properties are based on saturating the sample with water in a vacuum and the use of a pycnometer. The only thing necessary is an uncrumbled, representative fragment of wall. As there are no specific methods for rammed-earth walls, we selected two methods used for rocks that are extrapolable: RILEM TC 25-PEM (1980) and UNE-EN 1936:2007 standard.

### Determination of mechanical strength

Determining mechanical strength is fundamental to knowing the material's behaviour in service and its structural stability. Compressive strength is the property that reveals the most about the load-bearing capacity of rammed-earth walls. Many factors influence compressive strength: the components used, dosing of water and lime, means of execution, and deterioration factors over time.

Determination of the wall's compressive strength starts with the extraction of a test specimen (using one of the systems in the third section) considering these aspects:

(a) Orientation of specimen to compression. It should be oriented in the same direction as the wall compaction during its construction.
(b) Geometry. Test specimens can be cubic or cylindrical, but the best height/width ratio is 2. These parameters should be indicated since the compressive strength obtained will be different despite being from the same wall.
(c) Size/diameter of test specimen. Taking as a reference UNE-EN 12504-1:2009 standard for concrete, the ratio between the maximum aggregate size and the test specimen diameter/edge should be over 3.
(d) Capping. The load planes should be plane-parallel and so should be levelled with sulphur mortar or cement in accordance with one of the methods proposed in Appendix A from UNE-EN 12390-3:2009 standard.
(e) Loading rate. Due to the similarity in mechanical characteristics, the rate established for mortars is proposed (50–500 N/s; UNE-EN 1015-11:2000 standard).

### Granulometry determination

Granulometry provides information on the aggregate used and the intended texture during the manufacture of the material, thus allowing a comparison between types of aggregates and technological processes. To determine it, a series of meshes of decreasing mesh spacing (geometric progression) are used. The mesh series to be used is that of the UNE-EN 12620:2003 standard for concrete aggregates, comprising mesh spacings of 63, 31.5, 16, 8, 4, 2, 1, 0.5, 0.25, 0.125, and 0.063 mm.

The main problem lies in the procedure to separate the aggregate from the binder to perform the granulometry test, which depends primarily on the amount of lime used as a stabilizer. In the case of walls made without lime, it should be taken into account that the mainly earthen composition will easily crumble in water. A method is proposed involving manual fragmentation of the wall sample with a rubber mallet to a certain size (8–12 mm) and then crumbling with water, dispersants, and mechanical shaking. When lime is present, the sample has traditionally been attacked with hydrochloric acid (Alvarez et al. 1999). The insoluble fraction remaining after the acid attack and subsequent washing to remove excess HCl primarily comprises siliceous aggregate (quartz) and silicate aggregate (feldspars, micas, amphiboles, etc.) as they are unaffected by the acid or clay minerals slightly modified (Alvarez et al. 1999). It must be taken into account that limestone aggregate fractions or other carbonate fractions in the earth can break down and cause variations in the real particle size distribution.

The analysis using sieve method is useful to estimate the granulometry for lime stabilized rammed-earth (González López et al. 2018). In case of rammed earth stabilized with lime, due to its similarity with mortars and lime concretes, the comparison with Fuller's series is useful to estimate the compactness of the samples. As we mentioned before, this analysis requires a previous acid attack and the resulting grain size would be in the range of 63–0.063 mm (Maniatidis and Walker 2003; Zhemchuzhnikov 2015).

For non stabilized rammed earth, with a high clays content, the fraction under 0.063 mm (silt, 0.06–0.002 mm and clay, less than 0.002 mm) is significant and it is relevant to estimate the granulometry of fine particles. In this case, the most appropriate method for the identification of fractions less than 0.063 mm is laser light scattering analysis, which allows to determine particle size under 100 nm and can be complemented, if necessary, by SEM (Azema et al. 2002; Michel and Courard 2014). The advantage of this method is that it allows a distinction between the individual particles and the agglomerates formed. Then these microscopic observations will be more easily compared to granular characteristics obtained by laser granulometry (Autier et al. 2013).

## Case studies to validate the new methodology: Almohade ramparts of Seville and Malaga

### *Sample description*

The Almohade ramparts in Seville and Malaga were chosen as case studies to validate the new method of characterizing rammed-earth walls. Figure 1 shows the sampling procedure at both ramparts.

+ Seville rampart (UE1), sample from the rammed earth in the Almohade rampart, twelfth century; archaeological dig at 122 Sol Street (Seville, Spain).
+ Malaga rampart (UE2), sample from the rammed earth in the Almohade rampart, twelfth century; archaeological dig at 3 Medina Conde Street in Malaga (Spain).

### *Specific new methodology*

Major and minor chemical components were analysed by X-ray fluorescence (XRF), using a Panalytical spectrometer Axios model, with an Rh tube for the element analysis of solid and liquid samples. The carbonate content was determined by Bernard's calcimeter according to UNE 103200:1993, with the aim of approximating the original amounts of lime in the rammed-earth wall. The mineralogical composition of

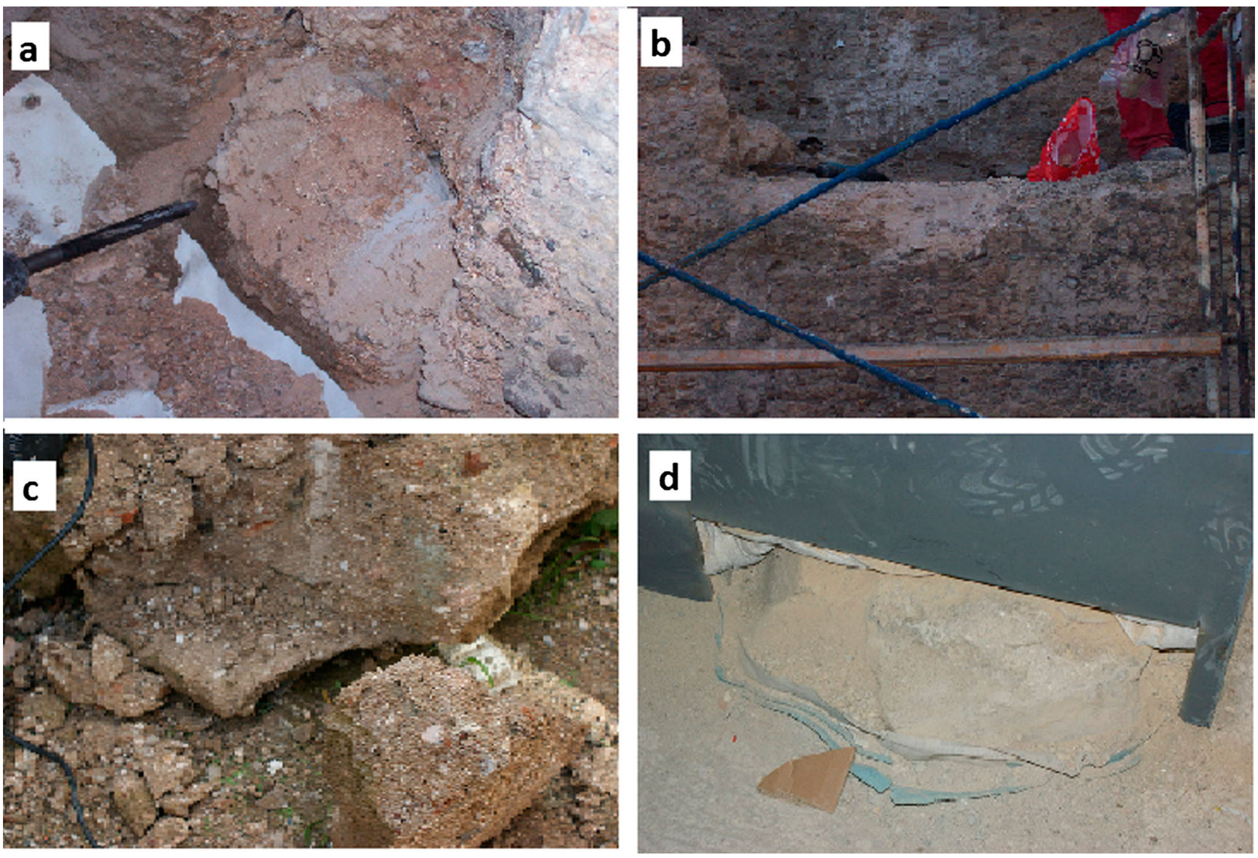

**Figure 1.** Areas sampled: UE1 (a, b), sample UE2 (c, d).

the samples was established by X-ray diffraction (XRD) using a Bruker-AXS D8 Advance diffractometer equipped with a copper filament, CuKα radiation, tube conditions of 40 kV and 30 mA, fixed slot, and sparkle detector. The diffractograms were obtained using the powder technique. XRD patterns in $2\theta$ range 3°–70° were acquired applying a 0.03° step scan with a 1 s step. A LEICA S8 APO optical microscope was coupled with a LEICA DC300 camera and IME 50 (image manager) software to capture the microphotographs. Apparent density and open porosity were calculated through the vacuum method according to EN-1936 (2007). Mechanical strength under compression was determined with cubic specimens 6–10 cm per side depending on the rammed-earth sample taken (two test specimens for each rammed-earth sample). The specimens were then capped with a 1:1 cement mortar, and the surface was calculated precisely before breakage. Rammed-earth samples were broken, using a strength-testing machine TCCSL model PCI-30 Tn., in accordance with UNE-EN 1015-11:2000 norm. In the particle size distribution analysis, samples were attacked with cold 36.5% HCl and washed with water several times. Finally, the fractions were separated with mesh screens sized in accordance with the UNE-EN 12620:2003 standard.

## Results and discussion

### Chemical and carbonate analyses

The chemical composition for the major elements is presented in Table 1.

When the chemical analysis results are compared in this type of sample, it is basically important to keep in mind three values. (1) The $SiO_2$ content, which is attributable in large part to quartz and other aggregate silicates used in the wall manufacture. In the examples, sample UE1 has twice the concentration as UE2. (2) The CaO content and the loss on calcination (LOI), primarily attributable to the $CaCO_3$ content in the carbonated lime or in the limestone fraction of the aggregate. UE2 has higher concentrations than UE1. (3) The $SO_3$ content, which is low (0.02% for UE1 and 0.55% for UE2), indicating gypsum was not used as a binder in either wall. Carbonate content (expressed as $CaCO_3$) are presented in Table 2, comparing them with reference lime mortar values.

The analyses on the two samples show a considerable difference in the carbonate content. Sample UE2 seems to have been mixed with a maximum lime:sand ratio by weight of around 1:4. In contrast, UE1, with lower carbonate content, would have had a maximum ratio of 1:12, revealing it to have been a poorer rammed-earth wall, manufactured with less than half the amount of lime. Note that this analysis cannot distinguish between primary (or original) $CaCO_3$ from the earth/aggregate from $CaCO_3$ deriving from the lime carbonation. Consequently, the amount of lime added to the wall can be overestimated.

The results of the chemical analysis are quite complementary with those for carbonate concentration as lower CaO and LOC indicate lower concentrations of $CaCO_3$ and higher aggregate concentrations as occurs in sample UE1. In contrast, higher CaO and LOI point to higher concentrations of $CaCO_3$ and lower aggregate ratios, as occurs in sample UE2.

**Table 2.** Carbonate content.

| Sample | (%) $CaCO_3$ | Reference mortars | |
|---|---|---|---|
| | | Proportions by weight (lime:sand) versus $CaCO_3$ | |
| | | 1:3 | 37.3% |
| UE1 | 12.6 | 1:4 | 30.8% |
| UE2 | 30.9 | 1:6 | 22.9% |
| | | 1:10 | 15.1% |
| | | 1:12 | 12.9% |

**Table 3.** Mineralogical composition by XRD.

| Minerals (abbreviations after Kretz 1983) | UE1 | UE2 |
|---|---|---|
| Quartz (Qtz) | ++++ | +++ |
| Calcite (Cal) | ++ | +++ |
| Dolomite (Dol) | – | + |
| K-Feldspars | | |
| Orthoclase (Or) | + | – |
| Plagioclases | | |
| Anorthite (An) | – | + |
| Phyllosilicates (Phy) | + | ++ |

Notes: ++++: very abundant; +++: abundant; ++: middle; +: traces; –: not detected.

### Mineralogical analyses: XRD of rammed-earth walls

The minerals identified and their qualitative abundance are shown in Table 3. Most of the mineral phases in the two wall samples are very similar. Quartz, K-feldspars (orthoclase), plagioclases (anorthite), and phyllosilicates (illite, chlorite, and muscovite) derive from the aggregate, whereas calcite may derive from the earth or the lime used in the manufacturing process.

### Optical microscopy

The images are presented in Figure 2. Note the lime nodules and the typical plastic shrinkage fissures

**Table 1.** Chemical composition (%) of samples form the wall.

| Sample | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | $SO_3$ | Cl ppm | LOI | Total % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UE1 | 61.41 | 6.57 | 2.35 | 0.05 | 0.75 | 11.99 | 0.86 | 1.50 | 0.28 | 0.20 | 0.02 | 0.04 | 11.53 | 97.53 |
| UE2 | 32.38 | 6.72 | 2.74 | 5.94 | 5.94 | 25.35 | 0.43 | 1.86 | 0.30 | 0.51 | 0.55 | 981.5 | 22.05 | 99.13 |

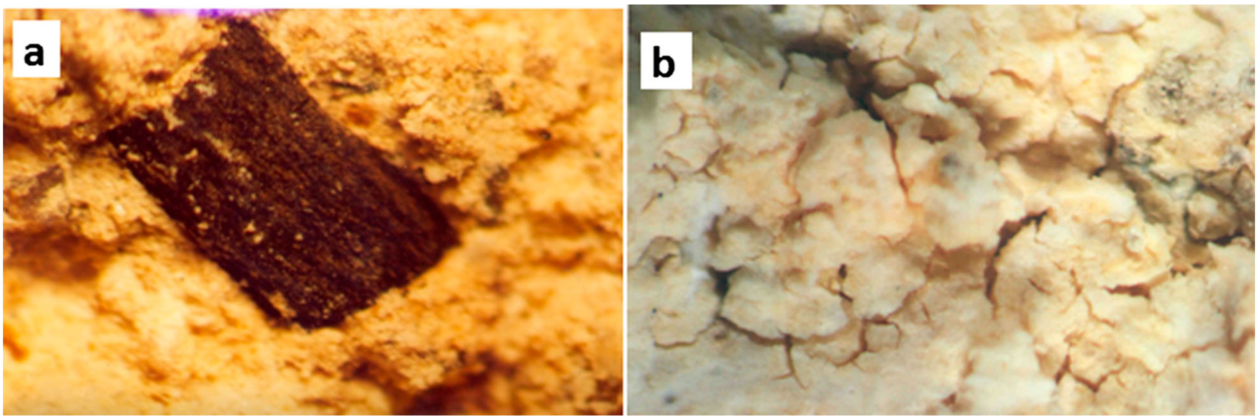


**Figure 2.** Microphotographs of a charcoal fragment (a), and plastic retraction microfissures (b) in various rammed-earth walls.

caused by the evaporation of the batching water. This is clear evidence of the addition of lime to the aggregate/earth during manufacture. Observe also the occurrence of plant charcoal nodules.

**Table 4.** Porosity and compressive strength of the rammed-earth samples.

| Sample | Real density (gr/cm$^3$) | Apparent density (gr/cm$^3$) | Porosity (%) | $R_c$ (N/mm$^2$) |
|---|---|---|---|---|
| UE1 | 2.58 | 1.81 | 29.8 | 14.9 |
| UE2 | 2.65 | 1.58 | 40.4 | 3.9 |

### *Physical properties: apparent density, porosity accessible to water, and compressive strength*

The real density values are as expected given the real density of the major elements comprising the samples: quartz at 2.62 g/cm$^3$ and calcite at 2.71 g/cm$^3$. The porosity values for this type of material range from 30–50% (Martín-Del-Río et al. 2008), and usually over 35%, so they are generally classed as very porous materials.

The porosity value of 29.8% in UE1 reveals it to be a rammed-earth wall with low porosity, indicating the rammed-earth wall was built with a low amount of water, good compaction with a rammer, and adequate particle size distribution in the aggregate.

In contrast, the porosity of sample UE2 is 40%, ranking it as a wall with medium to high porosity. The high porosity (>40%) can be accounted for by the presence of a fine fraction of Ø<0.063 mm in the raw materials (lime, clay minerals, etc.). These types of components are characterized by a high specific surface, which requires a large amount of water in the batching. It should also be noted that it was common to use such high amounts of water in batching in order to obtain greater workability. In both cases, when the water evaporates, it leaves open porosity.

The lower porosity and good particle size distribution in UE1 may have improved its mechanical behaviour despite the use of less lime. This underlines the importance of undertaking mechanical tests whenever possible to verify the behaviour. The results for the samples are given in Table 4.

The mechanical strength value for sample UE1 is very high for a rammed-earth wall, as they usually are in the range of 2–15 N/mm$^2$ (Martín-Del-Río et al.

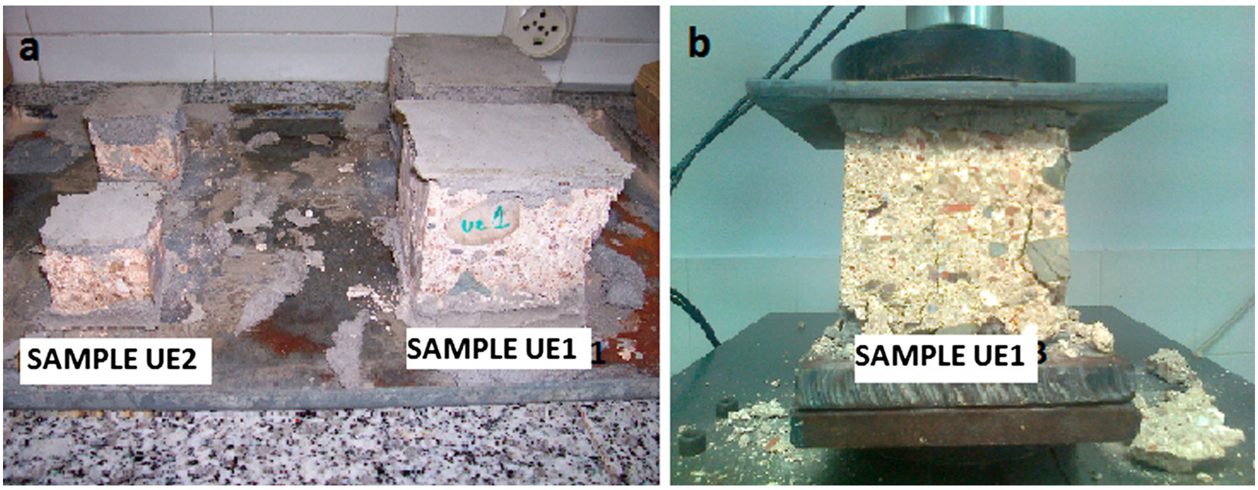


**Figure 3.** Photographs of two wall test specimens capped with cement mortar from samples UE1 and UE2, and the breakage of the UE1 specimen.

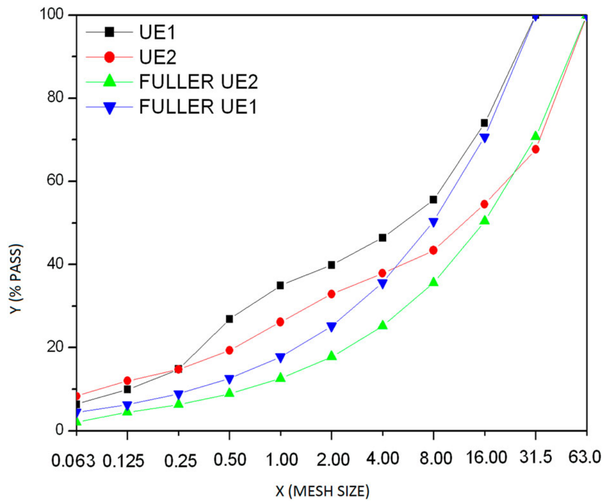


**Figure 4.** Particle size distribution in the two wall samples compared to Fuller.

2008). Sample UE2, in contrast, has lower mechanical strength than expected from its estimated lime ratio. Clearly, its high porosity has strongly influenced this parameter (Figure 3).

### *Particle size distribution*

The particle size distribution analysis (Figure 4) indicates that the aggregates in the two wall samples (UE1 and UE2) are finer-grained than the Fuller maximum compactness ideal. The maximum aggregate size is 31.5 mm for UE1 and 63 mm for UE2. In both walls, the aggregate fractions recovered from all the screen mesh sizes given in UNE EN 933-1 standard (0.063, 0.125, 0.250, 0.50, 1.00, 2.00, 4.00, 8.00, 16.00, 31.5, and 63 mm) are finer than recommended for maximum compactness.

Sample UE2 is less compact than UE1 as its particle size distribution module is 4.09 and it is farther from its Fuller maximum compactness curve of 6.68. In sample UE1, the module is 5.02 and the corresponding Fuller curve is 5.72. This difference in values between the particle size distribution module and the Fuller curve in sample UE2 is revealed in its higher porosity and lower compressive strength. However, the closer values for these two factors in UE1 reflect lower porosity and greater compressive strength.

## Conclusions

A new systematic method for characterizing historic rammed-earth walls is proposed, adaptable to the specific characteristics of each rammed-earth wall studied. The diversity and characteristics of these materials encourages project members (historians, archaeologists, restorers, architects, etc.) to demand detailed data on the archeometry and construction technology to aid in their classification and comparative study by providing information on composition parameters, physical and mechanical properties, particle size distribution, dating ranges, and so on. The possibility of recurring to such a wide range of techniques provides fundamental data for decision-making in any intervention involving maintenance, restoration, or rehabilitation.

Application of the proposed methodology to samples from the Seville UE1 rampart and the Malaga UE2 rampart has revealed compositional, physical, and mechanical differences between the two. Despite its hypothesized lower percentage of lime, the Seville wall has less porosity and better particle size distribution, which has resulted in greater compressive strength than the Malaga rampart. Furthermore, the lower porosity of UE1 is directly related to the use of a drier mixing batch. This method has supplied data on the materials comprising the rammed-earth walls, their structural characteristics, and mechanical properties. C14 has aided in confirming the hypothesized dating of the wall for sample UE2.

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## Disclosure statement

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