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An investigation of Roman mortar technology through the petrographic analysis of archaeological material

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Abstract

This paper studies Roman mortars to demonstrate that petrographic analysis provides valuable information on ancient mortar technology. Facts on lime technology relating calcination and slaking were obtained through petrographic analysis. The analysis also revealed the composition and origin of raw materials, pozzolanic additions and mortar hydraulicity. The results were contrasted with ancient Roman technology records including Cato, Pliny, Vitruvius, Palladius and Faventinus. The binders' petrofabric suggests a high reactivity and water retention capacity and a low shrinkage for the lime. These agree with the long slaking and soft burning advised by the Romans. The strong binder cohesion and perfect aggregate-binder bond of most mortars together with the presence of aggregate-binder reaction denotes a high reactivity for the lime which also agrees with soft burning. The mortars were probably made with a non-hydraulic or feebly-hydraulic lime and their hydraulicity is mainly due to the addition of pozzolans (ceramics). These agree with Roman authors consistently advising to use a pure carbonate rock for lime making. The pozzolanic additions are probably responsible for the good durability of the mortars.

Keywords: Mortar technology; Lime; Petrographic analysis; Hydraulicity; Pozzolan; $Ca(OH)_2$; Roman mortar

1. Introduction

This paper demonstrates that petrographic analysis of historic mortars provides fundamental information on mortar technology. The results arising from petrographic examination can be used today to fabricate quality repair mortars compatible with their adjacent masonry [1]. Samples of Roman mortars ranging in age from 100 BC to 500 AD were analysed with a petrographic microscope and the results compared to Roman records on mortar technology. The petrographic microscope is an important tool in geology and archaeometry which can be used to identify sources of raw materials and to attribute stone artefacts to their geological source [2]. It is also an essential tool in building material science in order to study the composition, size and shape of mineral grains and matrices; their relationships and arrangement; their decay and the presence of pores, cracks, cements and directional textures [3]. The technology of lime production determines the durability and properties of a lime mortar. For example, calcination and slaking are very important operations in the manufacture of building limes as they govern properties such as lime reactivity, shrinkage, density and water retention capacity, which in turn determine workability, plasticity and carbonation speed [4]. It has been demonstrated that underwater storage following slaking of quicklime improves plasticity and workability of limes due to particle size reduction and morphology changes [5]. Long slaking has also been associated to an increase in the water retention capacity of lime thus facilitating carbonation therefore enabling development of an early strength and improving mortar durability. The nature of the raw materials also determine the properties of and

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durability of mortars. For example, the presence of magnesian lime and/or reactive aggregate can impart a hydraulic set and therefore determine the quality of a mortar [6].

2. Materials and methods

Twenty six mortars ranging from 1500 to over 2000 years in age, originating from thirteen structures from six different locations in La Rioja, Spain, were analysed. The mortars fulfilled different functions within the built fabric. The samples were dated by archaeologists 'in situ' by means of archaeological methods. Fragments were selected for thin section preparation and petrographic analysis. Table 1 includes details of the samples. Given the age of the mortars and their limited availability, especial care was taken during thin section preparation in order to preserve the material. The mortars were pre consolidated by impregnation in a resin under vacuum. Thin sections were then cut with oils to avoid damaging water-soluble minerals in the mortars. They were polished to the standard thickness of 20 μm, covered with a glass slip and examined with a petrographic microscope incorporating eye pieces of 2, 10, 20 and 40 magnifications using both natural and polarised light.

3. Results and discussion

3.1. Petrofabric of lime binders vs. lime making technology

Petrographic analysis evidenced that the mortars studied, especially plasters and renders, possessed homogeneous, cohesive binders displaying a strong binder-aggregate bond and an absence of over-burned and under-burned lime particles. The lime binders are fine-grained rarely displaying fractures. These features can be observed in Figs. 1–4. Evidence of aggregate-binder reaction was found in several mortars and the presence of ceramic fragments acting as pozzolans was also recorded (see Figs. 1–4). Petrographic analyses revealed that approximately 85% of the mortars studied display unweathered binders which continue fulfilling their role.

In the mortars analysed, the fine-grained lime binders possess a high specific surface. In addition, the absence of binder cracks indicates a low shrinkage. The lime's high specific surface and low shrinkage suggest that the raw limestone was soft-burned. According to Boynton [4], lower burning temperatures and/or shorter burning duration (soft burning) yield the desirable soft-burned, highly reactive limes of low shrinkage and density and high porosity whereas a high burning temperature and long calcining

Table 1
Characteristics of the mortars studied

Sample or sample group	Mortar type/function	Age	Function of the structure holding the mortar
Geographical Location: *Contrebia Leukade, Aguilar del Río Alhama, La Rioja., Spain*			
RCL1	Pointing ashlar masonry of tufa and sandstone	Early Roman empire I-II c. AD	Tower of defensive city wall
RCL2			Column of city wall doorway
RCL3			City wall, lower ashlar courses
RCL4			
Geographical location: *Mantible Bridge, Fuenmayor, La Rioja., Spain*			
RM1	Pointing sandstone ashlar masonry	Early Roman empire I–II c. AD	Bridge over the Ebro river, part of the Roman road connecting the Pyrinees with the interior of Iberia
RM2	Bedding sandstone ashlar masonry		
Geographical location: *Calahorra City, La Rioja., Spain*			
RC1	Grouting a mosaic	Pre-dates late Roman empire (IV c. AD)	Paving a room
RC2	Decorated plaster	Early Roman empire I to II c. AD	Back / interior yard
RC3	Plaster	Early Roman empire I to III c. AD	Monumental construction
RC4	Render		Large pool in thermal baths
RC5	Plaster		Part of a thermal complex
Geographical location: *Tirgo Town, La Rioja., Spain*			
RT1	Rendering mortar	Late Roman empire IV–V c. AD	Pool in a garden or thermal bath
RT2			
Geographical location: *Varea Town, La Rioja., Spain*			
RV1	Render	Late Roman empire IV c. AD	Possible living space
RV2	Plaster		
RV3	Revestimiento		Craftwork establishment
RV4	Decorated plaster	Early Roman empire I to III c. AD	Possible living space
Geographical location: *Inestrillas Town, La Rioja., Spain*			
I1	Pavement	Celtic I c. B.C. (Romanization in progress)	Man–made caves. A possible private dwelling with a defensive character

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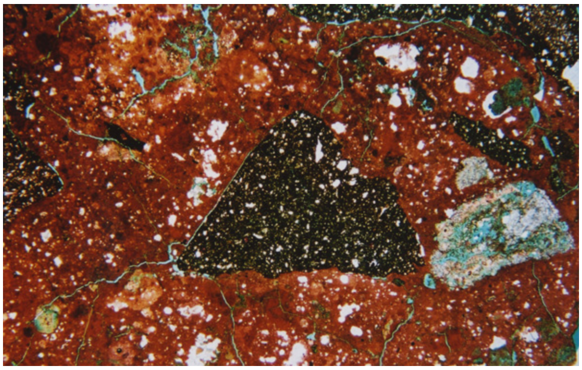

Fig. 1. Microphotograph of mortar I1 including angular ceramic aggregate in a fine-grained, homogeneous, cohesive binder of carbonated lime which remains unaltered. A perfect binder-aggregate bond is also evident. Plane polars 2×.

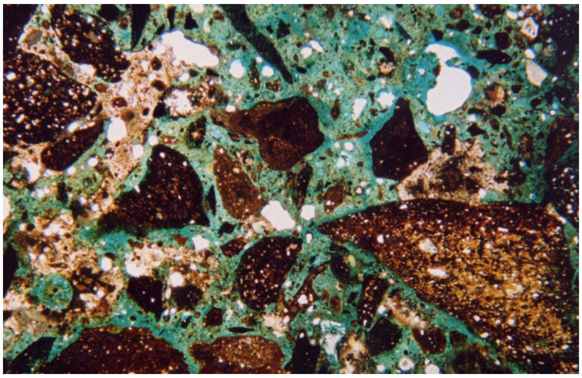

Fig. 2. General microfabric of mortar RV1 (finishing coat) including abundant angular ceramic fragments in a carbonated lime binder displaying the same properties as that in Fig. 1. Plane polars 2×.

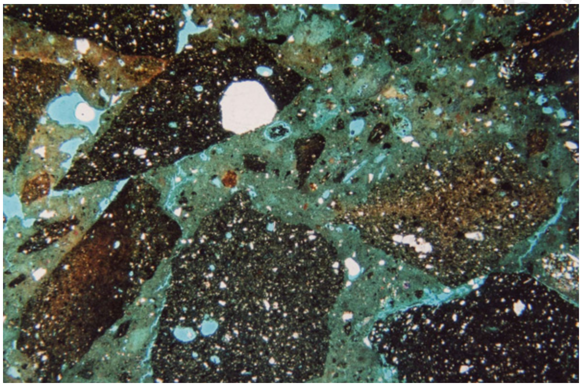

Fig. 3. Detail of finishing render coat (mortar RC5) including abundant ceramic aggregate in a fine-grained, cohesive lime binder. 2× natural light.

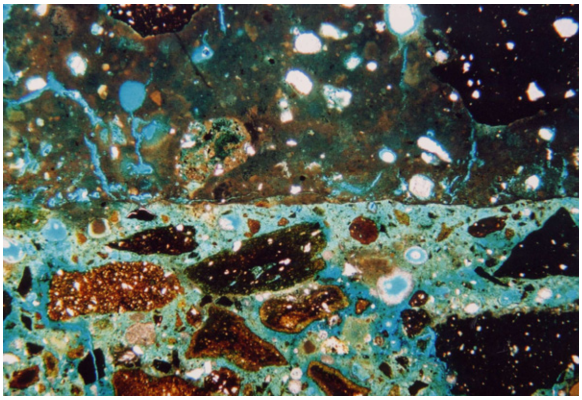

Fig. 4. Mortar RV1 contact interface between base and finishing coat (bottom). Both mortars include abundant ceramics and show a perfect aggregate-binder bond. 2× natural light.

periods result in a hard-burned quicklime that has high shrinkage, high density, low porosity and low chemical reactivity. Reactivity of lime refers to its quick ability to respond to chemical stimuli, e.g. reactive limes readily combine with water during slaking. The strong binder cohesion and perfect aggregate-binder bond of most of the mortars analysed together with the presence of aggregate-binder reaction denotes a high reactivity for the lime which also agrees with soft burning. Roman records on limestone calcination agree with the soft burning of the raw limestone deducted from petrographic analysis. The Romans refer to keeping the temperatures constant by looking after the operation and timing as well as protecting the kiln from the wind. Vituvius is extremely brief on lime making, however, Cato, writing some time before (around 160 BC), at a time when mortar bound masonry was becoming widespread, describes in detail the construction of a kiln and the burning of the lime [7]. Cato [8] refers to burning as follows: Be careful to keep the fire burning constantly, and do not let it die down at night or at any other time. Cato also refers to keeping the kiln temperature constant protecting it from the wind as follows: In building the kiln, make a bed so as to give it the greatest possible depth and the least exposure to wind. If you lack a spot for building a kiln of sufficient depth, run up the top with brick, or face the top on the outside with field stone set in mortar. When it is fired, if the flame comes out at any point but the circular top, stop the orifice with mortar. Keep the wind, and specially the south wind, from reaching the door. Cato [8] also advises on the timing for the burning operation: The calcining of the stones at the top will show that the whole has calcined; also; the calcined stones at the bottom will settle, and the flame will be less smoky when it comes out.

It is difficult to derive conclusions on lime slaking based on petrographic examination however, the even, fine-grained petrofabrics of the binders and the absence of over-burned and under-burned lime lumps indicate a good plasticity and workability for the lime, while the absence of fractures would be consistent with a high water retention capacity. The absence of unslaked lime lumps would also be consistent with a long, rather slow slaking (when a large water excess rapidly added lime is ‘downed’, its surface becomes hydrated and impervious to water penetration thus lumps are formed) [4]. As aforementioned, it has been demonstrated that long slaking periods improve the physical properties of lime including plasticity and workability, water retention capacity and carbonation speed therefore, the petrography of the mortars studied is consistent with a

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long storage. The Romans preferred lime which had been slaking for long periods. Pliny the Elder [9] reports that the builders of Rome were advised to use fat lime only after it had been left slaking for at least three years. The same author reports on lime slaking as follows: It is also a fact that the calx intrita (mixture of lime, sand and water) improves with keeping. In the old building laws is to be found a regulation that no contractor is to use a calx intrita that is less than three years old. Consequently, old plaster work was never disfigured by cracks. According to Vitruvius [10], the lime was to be slaked during a long time to allow non-fully-calcined limestone lumps to hydrate and acquire a fine, homogeneous consistency. The author considers this essential in plasters and claims that, when the lime was slaked during a short time, it contained lumps which would fracture as the plaster dried off causing cracks to appear.

3.2. Nature of the raw limestone. Mortar hydraulicity and pozzolans

All the mortars studied are hydraulic: the structural pointing and bedding mortars are slightly hydraulic while the paving mortars, as well as some of the renders and plasters are emminently hydraulic. However, according to petrographic analysis, most of the mortars were made with non-hydraulic lime and their hydraulicity is due to the addition of ceramics which have acted as pozzolans. This agrees with Roman technology records as Roman authors consistently advised to use a pure carbonate rock for lime making, therefore, the quicklime obtained would have been non-hydraulic. For example, Cato [8] specifies on the type of limestone to burn as follows: Charge the kiln only with good stone, as white and uniform as possible. Vitruvius also advised to use a pure carbonate rock for lime making either marble (pure) or white limestone [10,11]. Pliny the Elder [9] also refers to the burning of pure limestone: As for lime, Cato the censor disapproves of preparing it from variegated limestone, for white limestone produces a better quality. Lime made from a hard stone is more effective for walling, while that made from porous limestone is more suitable for plastering. However, the presence of clay-bearing tufa in the aggregate and clay flakes within the mortar binder in some of the mortars studied (Figs. 5 and 6) suggest that these were made with a hydraulic lime. This is the case of the mortars at the city of Contrebia–Leukade, excavated in the tufa bedrock. Petrographic evidence suggests that here, the local tufa was burned for mortar making therefore producing hydraulic lime.

Ceramic fragments are often very abundant and, in some cases, they are replacing the aggregate. Microscopic analysis evidenced that all the mortars including abundant ceramic fragments were unaltered. This suggests that hydraulicity induced by the addition of ceramics is partially responsible for the good quality and performance of the mortar, a fact previously reported by former authors [12].

Fragments of fuel were occasionally identified in the majority of the samples (Fig. 7). Their sporadic presence suggests that they are accidental, probably due to contamination from the kiln fuel. This fact has also been reported by former authors [13,14]. Remains of organic fuel are often found in historic mortars, some have reacted with the lime forming additional cements therefore imparting some hydraulicity to the mortars [14]. An exception to the sporadic occurrence of fuel was found in a mortar base coat rendering a thermal bath (sample RC4). This mortar contains abundant, evenly distributed charcoal suggesting

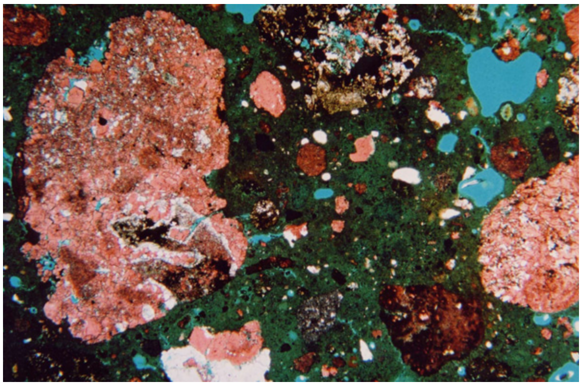
Fig. 5. General microfabric of Roman mortar RCL1 including large aggregate of local tufa in an abundant carbonated lime binder. 2× plane polars.

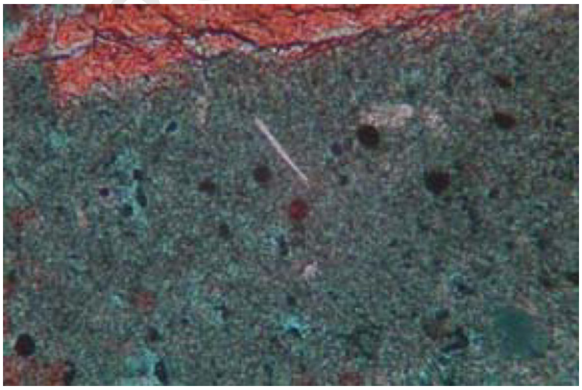
Fig. 6. Detail of calcite (micrite), clay minerals and iron oxides in the tufa aggregate of mortar RCL1. 10× plane polars.

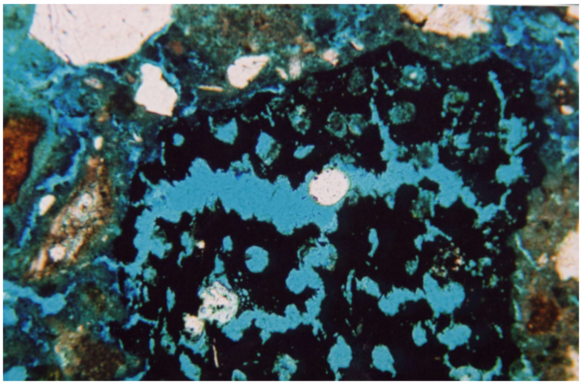
Fig. 7. Microphotograph of mortar RT1 showing the remains of fuel, probably charcoal. 10×. Plane polars.

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that, in this case, the fuel was deliberately added to the mortar as a pozzolan. However, no references were found in Roman records concerning the addition of charcoal as a pozzolan.

4. Conclusion

The fine-grained, cohesive petrofabrics of the lime binders studied, displaying a perfect aggregate bond, an absence of over/under-burned lime particles and scarce fractures suggest a high reactivity and water retention capacity as well as a low shrinkage for the lime. These agree with the long lime slaking/storage and soft burning of the raw limestone advised by the Romans. The strong binder cohesion and perfect aggregate-binder bond of most of the mortars analysed together with the presence of aggregate-binder reaction also indicate a high reactivity for the lime which also agrees with soft burning.

Petrographic analysis evidenced that there is no relationship between the social context and the quality of the mortars analysed. Most of the mortars are good quality materials no matter whether they were made for public and monumental structures or for more modest urban or rural dwellings. Material weathering usually progresses over time however, in the samples studied, no relationship was found between the age of the mortar and its current condition, and some of the eldest mortars were preserved the best.

Most of the mortars studied were fabricated with non-hydraulic lime and their hydraulicity is due to the addition of ceramics. This agrees with Roman technology records as Roman authors consistently advised to use a pure carbonate rock for lime making. Petrographic evidence suggests that hydraulicity induced by the addition of ceramics is partially responsible for the good quality and performance of the mortar. The conclusions above are based on a single analytical technique (petrographic analysis) so they may not be taken as final statements.

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