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An Experiment Measuring Water Consumption in Roman Hydrophobic Mortar (*opus signinum*)

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Opus signinum *is a lime mortar mix that includes crushed pottery as an aggregate. Because it is water-resistant, it was used to line hydraulic structures like pools and aqueducts. While there have been numerous recreations of Roman 'concretes' in the past, hydrophobic linings have received little attention, and all preliminary studies in these recreations have paid more attention to the dry components and the lime than to the hydric needs of the mortar. The experiment presented here was to gain a better understanding, with the help of traditional builders, of the process of mixing and applying hydrophobic linings and calculate the water consumption of individual samples. The data obtained contribute to assessing the water consumption needs on Roman construction sites, what associated logistics these volumes required, and what the technicalities of applying this specific type of lining were.*

Keywords: *opus signinum*, lime mortar, water, experimental archaeology, ethnography

Introduction

Our modern fascination with Roman concrete derives from the awe the sturdy elegance of structures like the Pantheon dome or the vault of Trajan's Markets in Rome inspire. These have survived to our day while modern concrete has a much shorter life span (Talukdar & Banthia, 2013). This awe fuels, in part, the myth of our incapacity to replicate Roman concrete, as if it were a long-lost art (Winter, 1979). Yet, we know a great deal about Roman concrete, as this material has been at the centre of many interdisciplinary research projects involving archaeologists, material scientists, and engineers (e.g. Oleson et al., 2004; Lancaster, 2005; Jackson et al., 2009; Brune, 2010; Oleson & Jackson, 2014; Seymour et al., 2023). The object of these studies has ranged from evaluations of the complex chemical interactions between lime mortars and volcanic dry aggregates to assessments of the physical and mechanical properties of Roman concrete structures. Roman concrete has also been at the centre of a parallel set of studies focused on the economics of Roman construction (DeLaine, 1997, 2017; Goldsworthy & Zhou, 2009; Camporeale, 2010). These studies have paid thorough attention to calculating the volumes and weights of the required materials, exploring their sources, quantifying the

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necessary work hours, and breaking down *chaînes opératoires* from quarry to site to extrapolate costs and economic impacts.

One essential element in mortar and concrete construction that has usually been overlooked in such studies has been its water requirements and the associated logistical problems. This may be owed to our modern reliance on easily accessible tap water, with no thought given to what impact water could have had on a budget. Moreover, it has been argued that the large number of variables for calculating water consumption in concrete mixing are too many to focus on water input (Brune, 2010: 18, 330; cf. Seymour et al., 2023: 5). It does not help that ancient authors do not seem to have been concerned by water sourcing or quantities either, even if they do acknowledge its importance (Lancaster, 2021: 21).

Yet, water is essential on any construction site, for mixing the mortar and slaking the lime, amongst many other processes. In large construction projects, this would have had a significant impact on time and resource management. Theoretical calculations suggest that a brick-and-mortar structure could require up to sixty per cent of its final volume as water input (Martínez Jiménez, 2022). This is a quantity substantial enough to make us wonder whether water was supplied to large construction projects in the same way as building materials (bricks, ashlar blocks, wooden beams) or dry aggregates (sand or pozzolana, a volcanic ash). Considering this gap in our knowledge, we set ourselves, within our AQUAROLE (the role of water in Roman production) research project, the task of finding a way to quantify water inputs in Roman mortar construction. This entailed working back from archaeological mortar to the mortar mixing *chaîne opératoire* and calculating the proportion of water added at the different stages of mixing. This would allow us to estimate the rough quantities of water needed to produce a given volume of mortar and thus consider the supply and storage logistics that were necessary on site.

For this purpose, we carried out an archaeological experiment during the summer of 2021 at the Museo de la Cal de Morón (Seville, Spain), in collaboration with traditional lime mortar builders. The objective was to recreate a type of lime-based mortar mixed with crushed terracotta used by the Romans for its hydrophobic characteristics and known by archaeologists as *opus signinum*, terrazzo or *cocciopesto*, even though the original name used by the Roman is unknown (Gros, 2013; Puche Fontanilles, 2019; Lancaster, 2021: 10–12). While this experiment is one in a long list of recreations of Roman mortars and 'Roman concrete', to date none of these had focused on *opus signinum*. Moreover, this is the first experiment in which the consumption of water has been the main scientific focus (cf. Oleson, 2014).

In this article, we present the premises and the first results of this experiment. After outlining the preliminary objectives of the project, the different stages of the experiment are explained, followed by a presentation of the information we obtained from the traditional builders who collaborated with us. We conclude by discussing how our experiment contributes to current studies on ancient concretes. The experiment has provided us with valuable information on a) empirically calculated ratios of water consumption in the mixing of lime mortars that use a crushed pottery aggregate, b) experimental data on the densities and other physical properties of lime mortars, and c) ethnographic insight into the process of mixing and applying *opus signinum* linings. These results set the foundations for the next stage of our project, which will compare the physical, mechanical, and chemical characteristics of our recreated mortars with archaeological samples.

Opus Signinum and Traditional Lime Mortars

Lime mortars are cementitious substances which rely on the lime cycle to bind larger building materials (rubble, bricks) together (Wright, 2005: 146–89; Hobbs & Siddall, 2010). The lime cycle is the process by which limestones ($CaCO_3$) are calcined to transform calcium carbonate into calcium oxide (CaO), also known as 'quicklime'. When quicklime is mixed with water, the resulting calcium hydroxide or 'slaked lime' ($Ca(OH)_2$) slowly absorbs CO_2 from the atmosphere while releasing water vapour, carbonizing back to calcium carbonate. These mortars are made of more sand than lime: sand adds volume and stiffness to what otherwise is a yoghurt-like lime putty (Cazalla Vázquez, 2002), but sand is an inert aggregate which, without lime, does not really bind (Oleson, 2010). This can be summarized as:

$$CaCO_3 \rightarrow CaO + CO_2$$

$$CaO + H_2O \rightarrow Ca(OH)_2$$

$$Ca(OH)_2\,(aq) + CO_2 \rightarrow CaCO_3 + H_2O\ (g)$$

Lime mortars have been used in building for centuries (Wright, 2005), but it was the introduction of pozzolanic sands to the mix in the last three centuries BC that led to the development of Roman concrete. This new pozzolanic mix was used alongside newly-developed building techniques, which included using standardized, pre-cut conical or pyramidal stones, brick production on a large scale, coffering to frame and shape mortar bound with rubble (*caementa*, which gave the term 'cement' and its cognates), and even different types of rubble of varying weights to improve vaulting techniques (Sear, 1982: 124–32; Mogetta, 2013). This initiated an architectural revolution which continued in the early Empire with further experimentation in vaulting and doming, and new materials (Lechtman & Hobbs, 1987; Lancaster, 2005; Van Oyen, 2017). Roman concretes with pozzolanic sands are mostly found in Italy or on projects linked to imperial power, like the Caesarea Maritima harbour works in present-day Israel (Hohfelder et al., 2007), but non-pozzolanic *opus caementicium* can be found anywhere across the Empire (Dix, 1982; Uğurlu Sağın et al., 2021). There has been plenty of research on the replication of lime-based Roman concretes (Goldsworthy & Zhou, 2009), but most experiments have focused on those that included pozzolanic ash (Oleson et al., 2004; Brune, 2010; UNILAD, 2021; Seymour et al., 2023), rather than on lime-sand mortars (Cazalla Vázquez, 2002) or, as in our case, lime and crushed pottery mortars.

What archaeologists call *opus signinum* (Figure 1) is a specific type of lime mortar that uses crushed terracotta or ceramics (chamotte) as its key dry aggregate. The addition of chamotte to the lime gives the mortar pozzolanic (i.e. hydraulic) properties, meaning that it can set under water and act as a hydrophobic lining (Vitruvius, *De architectura* 2.5.1; Oleson et al., 2004; Lancaster, 2005: 55; Rubio Bardon, 2011). *Opus signinum* was used across the Empire in water-related structures as a lining that kept dampness from damaging the fabric of whatever structure it was applied to, such as aqueducts, cisterns, swimming pools, fishponds, and industrial vats and basins. Since it forms a hard surface that could be smoothed, and it is a mortar with improved setting and curing times, it was not unusual to use *opus signinum* as bedding for mosaics (Izzo et al., 2016), as a polished floor surface (Vassal, 2006), and even as structural mortar in brick buildings (Šimunić Buršić, 2020). For these reasons and because few studies

Figure 1. *Roman* opus signinum *from a domestic cistern in Lucentum (Alicante, Spain). Note the remains of the smooth surface (left); smoothing closes the pores, thus improving impermeabilization. Here, the lining was applied on top of a base layer of sand-lime mortar.*

consider it, we chose to experiment with archaeologically reconstructed *opus signinum*.

The Experiment

Preparation: expertise and materials

The experiment was designed to replicate eight different *opus signinum* mixes combining different ratios of lime to sand to crushed pottery, based on the proportions suggested by Pliny (*Natural History* 36.173) and Vitruvius (*De architectura* 2.5.7) and by modern analyses of archaeological samples (Lancaster, 2005: 54–55, 2021, tab. 2; Siddall, 2010: 166). The mixes were chosen to obtain a range that could represent maximum and minimum water requirements as well as more standard mixing ratios that would represent more average mortars.

The next step involved using the ethnographic record to design a rigorous experimental work that could emulate the *chaîne opératoire* of mixing and applying *opus signinum*. Our intent was to conduct a scientific experiment that allowed evaluating and contrasting hypotheses, and identifying patterns for comparison (Morgado et al., 2011). For this, we relied on the expertise of a master builder, Luis Prieto, and his apprentice, Alejandro Ciudad, who helped us at all stages. Combining their expert input with our theoretical knowledge, it was possible to establish a dialectic relationship between them as builders and us as researchers (González-Ruibal, 2017; Rappaport, 2018).

We wanted to use materials that were as close to the Roman originals as possible to replicate accurately the work of ancient builders (Callahan, 1999) (see Supplementary Material, Table S1). For the chamotte, we obtained 60 kg of Roman ceramic building material. This had been discarded from the University of Granada's excavations at the Cartuja Roman kiln site. Roman *opera signina* used a wide range of ceramics material, including tile, but also kitchenware and Samian ware (Siddall, 2010). Since pottery from the excavations were to be deposited at the Archaeological Museum of Granada, we could only use (i.e. destroy) building materials that were to be discarded. We had to crush these tiles to obtain chamotte (Figure 2A), which we did with hammers of different weights and sizes. The resulting material was sifted and separated into two categories: coarse (<15 mm) and fine (<5 mm). On average, it took four people, working for four-and a-half hours to crush half a crate of tile (16.6 kg), giving a ratio of 0.92 kg/pers./hour.

For the lime, we collaborated with the Morón Lime Museum, who provided quicklime and matured slaked lime putty. Morón is the last place in Europe where traditional, pre-industrial, forms of lime burning still exist, and for this it was recognized as intangible cultural heritage by UNESCO in 2011. To date, three traditional lime kilns that burn limestone with olive wood are still in use. Traditional lime burning involves stacking

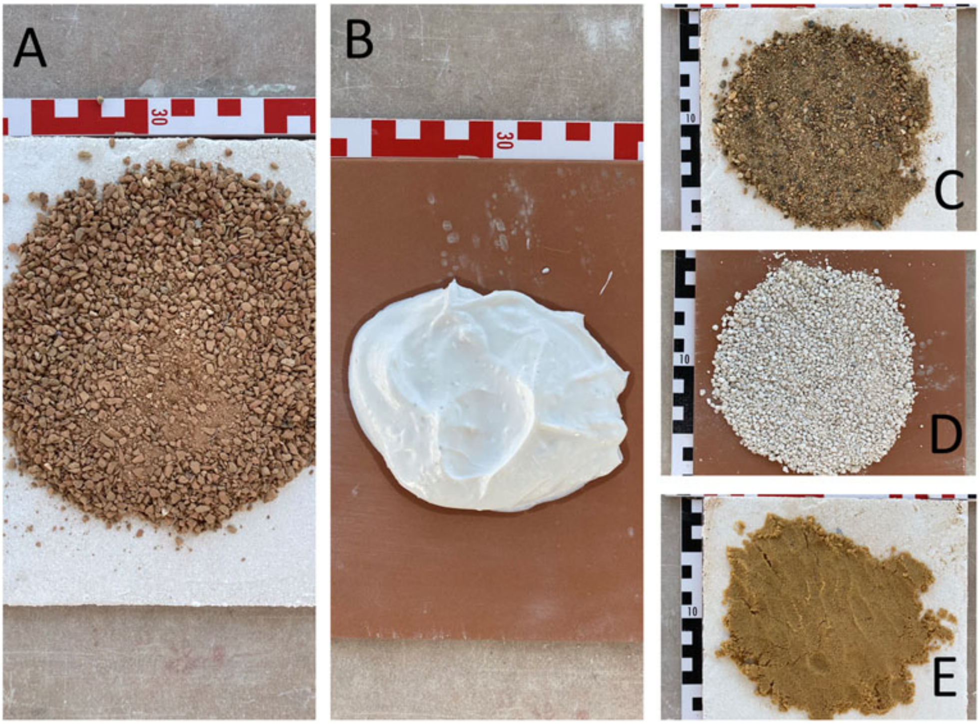

Figure 2. *Materials used during the experiment. A) recreated chamotte; B) lime putty; C) siliceous quarry sand; D) calcareous quarry sand; E) siliceous river sand.*

limestone rocks in rings several metres high inside a kiln, leaving a central space for the fuel. The pile of limestone is then covered with a temporary mud dome, and the fuel ignited. The combustion reaches temperatures of over 1000°C, and goes on for ten to twenty days, requiring lime burners to be constantly shovelling fuel into the furnace and treading down the mud dome (Carrera Díaz, 2015). The quality of the final quicklime depends on the type of limestone used (its overall calcium carbonate content), the temperature reached in the kiln, and the length of the burning process. The technical knowledge of the twenty-first-century Morón lime burners is similar to that of the Roman *calcis coctores* who used clay to protect the walls and carefully sorted the fragments of limestone around the kiln, and their *fornaces calcariae*, i.e. kilns twice as tall as wide and semi-buried (Cato, *De re rustica* 38.1–4; Petrella, 2008; Juan Tovar, 2014). This long, slow calcination with ligneous fuels gives quicklime a series of physical properties that are not matched by the calcium oxides obtained in industrial, short-burst, fossil fuel-powered kilns. The traditionally burnt limes have larger particles and pores, and a higher density of mesopores, which means that the slaking process is less exothermic and more water efficient (Ontiveros Ortega et al., 2018). This affects the way the lime mortars are made, making these traditional limes ideal for our experiment, as they are as close as possible to those the Romans would have originally used (Figure 2B).

The museum also supplied us with three types of commercially available building sands, sourced locally (Figure 2C–E).

For the experiment, we used tap water, piped from local calcareous springs but, as suggested by our master builder, we left it to 'rest' overnight to let the minerals and salts in the water settle (cf. Gárate, 2002: 99). Moreover, our master builder mentioned that heavily mineralized water causes mortars to 'sweat' salts, which form discoloured bands on the mortared surfaces (Vitruvius mentions beach sand causing the same: *De architectura*. 2.4.2). In the reconstruction of the pila (free-standing block) in present-day Brindisi harbour, the researchers opted to use seawater for their mixes, arguing that even if Vitruvius never specified that seawater was a viable option, it was an 'obvious logistical and economic shortcut' (Oleson, 2014: 108; see also Oleson et al., 2004). Ancient authors, however, also suggested washing sea sand, probably to remove extra salts and minerals (Lancaster, 2021). While we can assume that seawater could have been an option for mortar mixes in coastal areas, it seems preferable to use fresh water in *opus signinum* linings to prevent the salt from sweating. Be that as it may, nothing seems to indicate that the mixing proportions would have been different when using seawater.

We requested both lime putty and quicklime so we could use both the matured slaked lime and slake our own. We know that the Romans slaked lime on site in pits and vats (Dix, 1982), and it has been proposed that this was an *ad hoc* occurrence in large construction projects (Brune, 2010: 336), but we also know that they used the 'volcano' method of mixing hot mortar, which combines mortar mixing and lime slaking into one single process (Adam, 1994: 164; Oleson, 2014: 112; Lynch, 2017; Seymour et al., 2023). Our master builder suggested, based on his experience, that, since *opus signinum* is a lining and not a structural mortar, it was better to use the already-slaked lime putty. This is something that the Romans did too, as attested at the Casa della Soffita (V.3.4) in Pompeii, a house that was undergoing repairs, which contained a series of stacked amphorae with lime putty inside (Adam, 1994: fig. 160). At the Casa del Sacello Iliaco (I.6.4) in Pompeii, on the other hand, lumps of quicklime were stacked in preparation for on-site slaking (Lancaster, 2005: fig. 41).

The last preparatory step was to create a surface for our plasters. We decided to apply the *opus signinum* onto wooden-framed brick surfaces built for this purpose so we could easily measure, weigh, and transport the samples. The framed surfaces were built with eight modern, 'rustic'-type bricks (112 × 132 × 32 mm), similar in density and composition to those used in Roman times. These were bound with a simple gypsum plaster (that would not react with the lime mortar and would not absorb moisture from the samples) forming a square. The bricks were fitted into frames made with overlapping pieces of wood, which measured 528 mm on the outside and 465 mm on the inside. The bricks in the frames had a 20 mm gap on one side and a 10 mm gap on the other, meaning that each frame could hold two *opus signinum* samples of two different thicknesses. Eight of these frames were made over two days, each with enough space for 6.486l worth of mortar sample (with one face of *c.* 2.2l and another of *c.* 4.4 l). Once finished, the frames were weighed and their individual weights recorded. On average, they weighed 15 kg (Figure 3; Supplementary Material 1).

Mortar mixing and application

The experiment took place between 30 August and 5 September 2021. Temperatures averaged 26°C and the humidity was fifty-one per cent.

Figure 3. *Framed bricks, onto which we applied our experimental mortars.*

Figure 4. *Builder's scoop (capacity: 0.7 l) used for our measurements.*

The samples were mixed in a 30 l plastic tub. The ingredients were measured using a builder's scoop, which holds 0.7 l, and mixed according to the pre-calculated proportions (with fractions of a scoop given in decimal values) (Figure 4). The result was a very stiff mixture that, because of the large proportion of dry aggregates to lime putty, had to be kneaded—in many cases by hand and not just with a trowel (Figure 5). Water was added at this stage to make the mix more malleable, but never enough to make it runny (Vitruvius advises that mortar mixes should not stick to the trowel: *De architectura*. 7.3.6). It took ten minutes to mix these small amounts of mortar and, once mixed, the mortar was left to rest, usually for forty-five minutes. This allowed the dry aggregates to absorb moisture both from the putty and from the added water. Our chamotte, on average, can absorb twenty-nine to thirty-six per cent of its weight in water. Consequently, the final volume of the mix was smaller than the sum of the volumes of the separate ingredients. On average, this reduction in volume, which is not usually discussed in other recreated mortar mixes (Brune, 2010; UNILAD, 2021; but see Oleson et al., 2004: 219), was 63.04 per cent, with a range between fifty-two and seventy per cent.

Before the mortar was applied to the frame, the bricks and the wooden frames were soaked to the point of saturation, to minimize the absorption of moisture off the mortar into the support—a precaution that Vitruvius highlights for other mortar constructions (*De architectura* 2.8.2). Typically, each side of a frame (0.217 m^2) required a litre of water. Each square metre of brick surface therefore needed a minimum of 4.61 l of water.

The mortars were then applied to the frames. Depending on the consistency of the mix, these were thrown directly onto the bricks with a trowel or applied with a wooden float. The mortar was applied in a cycle of throwing, flattening, and then compressing with a trowel. Our master builder insisted that it was the act of compressing one layer onto another that gave these plaster-like linings their strength and durability, perhaps echoing Vitruvius' instructions about applying multiple layers when plastering a wall (*De architectura* 7.3.6).

The frames, once the mortar was applied, were left to carbonize in the shade, inside the museum's main building. The frames were weighed when 'empty' (i.e. before any mortar was applied), just after the mortar was applied, a day after its application, and three weeks later, each

Figure 5. *The four main stages of mixing and applying* opus signinum.

time recording the decreasing weights owed to the loss of water.

Results

The *opus signinum* sample

Since the objective of our experiment was to keep track of water consumption in mortar mixing to calculate the water input that can be reasonably extrapolated for dry mortars (Figure 6; Supplementary Material, Table S2), we identified a number of key traits:

1. The 'dry' or pre-mix water ratio (r_d) is the water (v_w) added to the mix in volumetric relation to the combined amounts (Σv_a) of lime putty and dry aggregates ($r_d = [v_w \div \Sigma v_a]\%$). Despite a wide range of water inputs (between 5 and 23 per cent of the volumetric sum of putty and dry aggregates), most mixes required a water input between eleven and twenty-one per cent of the sum of the pre-mix volumes. In our experience, the mix with no sand (just chamotte) was the 'thirstiest'. Siliceous sands are 'thirstier' than calcareous sands. In the presence of sand, the granulometry of the chamotte does not appear to have had an impact on the water requirements.
2. The 'wet' or post-mix water ratio (r_w) is the relation between the water input (v_w) and the final volume of mortar mix, which includes the volume used in the sample and the volume of leftover mix ($v_s + v_{lo}$), in percentage ($r_w = [v_w \div (v_s + v_{lo})]\%$). This was on average twenty-six per cent and, while there is again a wide range (between 8 and 45 per cent), most mixes required an input of water equivalent to seventeen to thirty-seven per cent of its volume. This range is slightly wider than the fifteen to twenty per cent that Adam (1994: 74) suggested from his theoretical work on lime mortars.
3. The water content in fresh mortars derived from the water contained in the putty itself tends to be lower, but more consistent across the different mixes

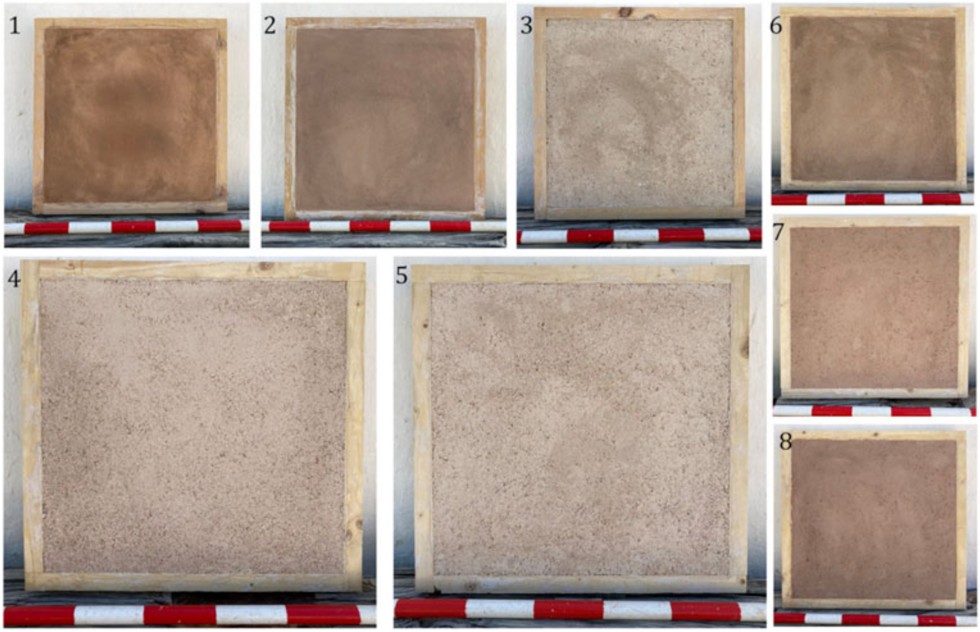

Figure 6. *Reconstructed* opus signinum *frames.*

(15–20 per cent) because most use similar ratios of putty to aggregates. Naturally, there is far more divergence when looking at the water input (8–45 per cent) used to correct the stiffness of the mix (rheologic water), as this varies according to the proportions, types, and accumulated moisture of the aggregates.

4. The rate of reduction in volume of the mix as the aggregates absorb moisture (r_r) is measured by comparing the volume of the separate ingredients ($\Sigma v_a + v_w$) against the volume of the sample ($v_s = 6.486l$) plus whatever leftover mortar (v_{lo}) there was ($r_r = [(v_s + v_{lo}) \div (\Sigma v_a + v_w)]\%$). In total, this apparent shrinkage ranged between fifty-two per cent and seventy per cent of the sum of pre-mix volumes, the average being sixty-three per cent. The mix that shrank the most was the mix without any sand, as expected; the chamotte is porous and absorbs more moisture, not just from the added water, but from the putty itself.
5. We were able to calculate that, on average, fresh *opus signinum* has a density of 2 kg/l, with a narrow range between 1.95 and 2.23 kg/l. Once dried, the density was reduced to an average of 1.5 kg/l, within a wider range between 1.28 and 1.68 kg/l.
6. The total content of water in fresh mortar (r_{tot}) is the sum of the wet ratio plus the water held in the putty in each mix ($r_{tot} = r_w + r_p$). The percentage of water in the putty (r_p) is sixty per cent of the volumetric fraction of putty (v_p) in the final volume of mortar ($r_p = [v_p \div (v_s + v_{lo})] \times 0.6$). Note that sixty per cent is the quantity of water in Morón lime putty, as given by the museum consultants; stoichiometrically, a 1:3 volumetric slaking ratio would give a water content in putty of fifty-four per cent (Martínez Jiménez, 2020). From the eight samples, we calculated that the average water content in fresh *opus signinum* was forty-five per cent, with a total range between thirty-three and

sixty-seven per cent, but with normal values between thirty-six and fifty-four per cent. The difference between the calculated percentage of water and the weight loss due to evaporation for each sample shows an average divergence of 0.23 l, i.e. the samples lost up to 800 g more than the calculated water they contained. While it is possible that this reflects residual moisture in the sand or chamotte, it most probably represents the evaporation of the water absorbed by the bricks and the wooden frame when these were sprinkled.

Vat slaking

On 1 September 2021, we slaked lime by adding water to rocks and nuggets of quicklime in a vat, as described by Vitruvius (*De architectura*. 7.2.2) and Pliny (*Natural History* 36.55). Traditionally, the process of slaking is in a volumetric ratio of 1:3 lime to water so that the lime not only changes from calcium oxide to hydroxide, but also turns into a putty that is left to mature. The process is well known and documented (Dix, 1982; Morgan, 1992; Wright, 2005), but we wanted to recreate it.

We prepared one bucket of quicklime rocks (8 l, and 9.1 kg, i.e. 1.138 kg/l) and three buckets of water, but, as we stirred the stones, it became clear that it would require more water if we wanted to achieve the yoghurt-like consistency of the paste used by the builders (Figure 2B), and half a bucket was added (total 28 l) so the ideal ratio for this specific type of quicklime was 1:3.5. This contrasts with the 1:2.1 weight ratio of Brune's (2010: 336) experiment, where the resulting slaked lime was a 'stiff but malleable paste, with no appreciable free water remaining in the mixing trough' and that the 'coherence of the paste made it impractical to measure its slump', noting that a 1:2 mix rendered the mixture 'unworkable' (compare with the recreation by UNILAD, 2021). This kind of stiff paste would have made the maturing of the paste suggested by ancient authors impossible (Lancaster, 2021; cf. other traditional approaches in Harper, 1934), since the excess water in the vats formed an airtight film that kept the slaked lime from carbonizing. This dryness would also prevent the later slaking of unslaked nodules of quicklime (cf. Seymour et al., 2023). Overall, we consider our more watery paste to be closer to what the Romans would have used.

We stirred it with bamboo canes, as the hot lime would have corroded any metal. The museum staff mentioned that this was a job traditionally undertaken by women, who often went blind because of the ejecta of the bubbling lime water. It took one minute for the water to start sizzling and bubbling, and four minutes until the water was fully boiling. In ten minutes, the rocks had all crumbled into small nuggets, but the mix took a total of thirty minutes to become a homogeneous putty cool enough to touch (cf. Brune, 2010: 337).

'Hot mortar' mixing

Hot mortar is a way of combining slaking and mortar mixing in one single process by making a heap of sand, putting the rocks of quicklime in it, and then slowly adding water to the lime, slaking it; hence its alternative name, 'dry' or 'volcano slaking' (Adam, 1994: 164; Lynch, 2017). Mosaics now in the Bardo museum in Tunis show Roman builders pouring water out of an amphora onto a pile of sand, perhaps an example of hot mortar mixing.

In our experimental recreation, we decided to use 3 l of quicklime in rocks and nuggets. Since we knew that the volume of the putty roughly doubles the original volume of quicklime during the slaking process, we expected to obtain 6 l of putty. With a 1:3 lime to sand mix in mind, we created a pile using 18 l of siliceous river sand. This sand had not been left to dry and was still moist. A hole was dug on top of the heap, the quicklime was put into it, then we slowly poured water, which was mixed with a bamboo cane. The lime had, in any case, begun to absorb moisture from the sand, and it formed a layer of slaked lime that lined the cavity, so that, even as we stirred the bubbling lime water and melting rocks, no sand crept in. In total we used 9 l of water, which would suggest a 1:3 quicklime to water slaking ratio; if we consider the moisture of the sand, we probably had the 1:3.5 ratio that we calculated for the vat slaking. Just as in the previous experiment, it took roughly thirty minutes to complete the slaking, although this slaked paste felt slightly thicker than the paste we had made in the vat.

The resulting putty was left in the 'crater' of the sand volcano for three hours, to allow the smaller nodules of quicklime to continue slaking. Then the putty and the sand heap were mixed together with a hoe. The builders told us that there was no need to add extra water, since the consistency of the mix was 'perfect' (Figure 7).

Interview With a Master Builder

The experiment would have been impossible to conduct without the invaluable help of two traditional builders with years of experience in lime working, even though they had never undertaken any archaeological reconstructions. They belong to a line of craftsmen who have transmitted their specialized knowledge and know-how for generations. Observing their hands-on knowledge has allowed us to appreciate from a scientific perspective the gestures and patterns not discernible from ancient sources or analytical data. Their skill in mixing and applying the mortars was recorded in video, photographs, and field notes. After the frames were finished, we invited master builder Luis Prieto and apprentice Alejandro Ciudad to exchange views and thoughts on the experiments, in a semi-structured ethnographic interview (Guber, 2001: 75–100).

Our major questions concerned the different mixes and proportions we had used. We wanted to know if they thought these were adequate or if, based on their experience, the mixes would not be useful in construction works. They first told us that they had decided to collaborate with us because they thought that our proposals (even though we were academics, whom they consider people who work with 'theories and abstracts' and no real knowledge of 'real life') looked promising, on paper. They then said that all our mixes would be useful but that each would have served different purposes: some would have been better for linings while others would have been better as binders or beddings, all depending on the size of the aggregates. They singled out the hot mortar (about which they initially were sceptical) as good only for mortaring rubble and foundations but not for linings because small, unslaked nodules of quicklime might slake later on and liberate heat and gas. This proved to be the case: the hot mortar sample that was applied to the framed tile shows small bumps on its surface, resulting from the explosion of these lime nodules.

Concerning water consumption, we asked if they thought that builders in the past would have been as precise as we had been in measuring the water ratios used in the different mortar mixes. They answered that their work cannot be understood from purely 'scientific perspectives and millimetric percentages'. They insisted that it was not

Figure 7. *Recreation of a hot mortar.*

an exact science, and that it depended on the purpose and circumstances. In their words, 'the water for the mortar is the builder's sweat'. This must be understood as relatively stiff mortars (despite the use of lighter lime pastes), which contradicts the practice followed in modern restorations, where runnier mortars are favoured (Cazalla Vázquez, 2002). The master and his apprentice also suggested that lime mortars could use any water (unlike gypsum plasters which must be mixed with clean water). This opens the possibility that 'grey' or runoff water from fountain basins or *castella* (distribution tanks) that ran into street drains (Frontinus, *De Aquaeductu* 94.3 and 111; Lex Ursonensis 100 (=*CIL* II^2 5, 1022; *CIL* II 5439); Varro, *Rerum rusticarum* 3.5.2) could have been used in construction projects.

For aggregates, we asked what impression they had gained from using chamotte made of Roman pottery, rather than industrially fired ceramics. They emphasized how surprised and impressed they were with the physical properties of the chamotte we used, saying it was 'like water and wine'. In their opinion, using archaeological chamotte resulted in mortar mixes that were stronger, firmer, more malleable, and homogeneous than any lime mortars they had worked with, creating an ideal granulometric curve. The setting times were also improved; they had never worked with lime mortars that were ready to apply in thirty or forty minutes. Despite this, water consumption appeared to be roughly the same.

The main difference between historic and modern chamotte is the different chemical properties. Ancient ceramics fired at lower temperatures (usually 750°C) give lime mortars pozzolanic properties (Oleson et al., 2004; Lancaster, 2005: 51; Pavía & Caro, 2008; Hobbs & Siddall, 2010; Marín Díaz & Dorado Alejos, 2014). These ceramics would also have been fired using wood and olive stones as fuel, all of which would have transmitted certain properties to the pottery that modern kilns cannot replicate. Modern ceramic building material, by contrast, is manufactured in 'conveyor belt' kilns, using fossil and biofuels (olive waste) that do not fully fire the clays. Moreover, these chamottes are crushed out of bricks made with clay mixes with a higher sand content, making them more voluminous but lighter (Vázquez & Jiménez Millán, 2004; Galán & Aparicio, 2005; Cárdenas & Agudo, 2012), unlike the denser, more clayey Roman bricks.

With respect to the application of *opus signinum*, we enquired about the gestures, tools, and abilities that would result in a good terracotta-and-lime lining. Luis Prieto and Alejandro Ciudad insisted that applying multiple layers was the key to a durable lime mortar lining, but they warned that because these layers are trowelled while the mortar is still fresh, it is unlikely that they would be noticeable in microscopic analyses. They impressed on us that compressing the mortar layers (*repretado* in Spanish) with a float or trowel was an essential part of the process, and mentioned that they could have polished the surfaces to a neater finish with a rolling stone, which would have made it completely watertight by closing all pores (Figure 8). They added that the improved properties that the historic chamotte gave lime mortars, especially the improved firmness and setting times, made these *opera signina* perfect for polishing into smooth flat surfaces. This, we believe, must have been key in Roman water-related constructions, because even if the chamotte already gave the *opus signinum* hydraulic properties, it was the trowelling and the polish that made the linings hydrophobic.

Since we usually see Roman *opera signina* eroded by time, it was difficult for us to envisage *opus signinum* linings as flat surfaces. When we raised this issue, we were shown how the recently polished surface of Frame 5 could easily be wet-brushed so that the finer polish was washed off. This technique, usually applied to modern terrazzos for aesthetic reasons, resulted in an irregular off-white surface with specks of red and orange resembling 'archaeological' *opus signinum*. However, since we were using tiles, the colour was not as bright red (or even pink) as in other archaeological *opera signina*.

Finally, we asked more technical questions regarding the application and polishing of plaster in aqueduct conduits, considering that most were either U-shaped or had quarter-cylinder reinforcements in the corners (box-shaped conduits; Sánchez López & Martínez Jiménez, 2016: 43–45). Their 'most reasonable' suggestion was that these linings would have been applied with a float and trowel but then polished and shaped using a wooden mould (*terraja* in Spanish) guided on wooden runners.

Figure 8. *Polished* opus signinum *surface repelling water droplets. Note the trowel marks left in the process and the rougher, washed off surface, showing the difference between original finish and 'archaeological' state.*

Discussion and Conclusions

Based on our original expectations, the experiment was a complete success. The expert input of the master builders was paramount, and the ethnographic aspect of the experiment cannot be stressed enough. We were able to calculate the water input at different stages of *opus signinum* mixing for a variety of aggregate and putty mixes under careful and expert supervision, hoping to achieve an experience as close to the Roman original as possible. The results give us a first indication as to the volume of water consumption in ancient constructions.

Opus signinum was present all over the Empire, and its use shows that building techniques and specialized knowledge were transmitted through apprenticeship. The requirements of matured lime putty tell us that construction projects involving *opus signinum* probably called for local lime burners to have a readily available supply of matured slaked lime. Larger construction projects could have consumed quicklime that was mixed and slaked on site; since *opus signinum* linings were usually the last elements added, it would make sense to use the putties slaked for general purposes at the beginning of a project and left to mature. In terms of water consumption, and since *opus signinum* required pre-slaked putties, each cubic metre of applied hydrophobic mortar would have required between 0.1 and 0.45 m^3 of water available for mixing on site.

The numbers given here, especially those related to water volumes, should not be taken as universally valid quantities. Different dry aggregates would demand different volumes of water, as would different climate conditions. This first study can nevertheless provide indicative ranges of water needs, essential for including water in debates around the economy of construction and the quantification of materials in Roman times (cf. Snyder, 2020). For example, the lining of the *fossa* of the Roman amphitheatre of Mérida (cf. Sabio González, 2020), with an approximate volume of 27.22 m^3, probably required between 4 and 10 m^3 of water (see Supplementary Material 2). This range constitutes a first step towards evaluating the logistics and economics of building in *opus signinum*.

The different recipes have shown us the great versatility of this material, which, depending on the purpose it served, would have been mixed with coarser or finer aggregates. The key element in applying *opus signinum* linings was to compress them with a trowel and float. This redistributed the granulated aggregates and the lime matrix, eliminating any gaps or vacuoles that might have formed and closing the pores to ensure a smooth and watertight surface. Vitruvius (*De architectura* 2.4.3) also notes the importance of trowelling (*liaculoarum subactionibus*). Pliny (*Natural History* 36.55) and Vitruvius (*De architectura* 7.3) both refer to the application of multiple layers of plaster. Perhaps we should understand that these mentions do not refer to the number of layers, but rather to the repeated gesture of compressing and polishing the surface with a float or trowel.

This importance of trowelling and smoothing the mortar (*repretado*) to improve the properties of a lining are directly related to the stiffness of the mixes, the water input, and the consistency of the lime pastes. Lime pastes need not have been runny; in Roman times they were probably not used when 'stiff but malleable' if they were to be compressed. We must keep this in mind in future studies and recreations of Roman-style mortars.

Our experiment has underlined the importance of water in Roman urban contexts at a broader level. Cities were permanently under construction, and in the early Empire this involved recurrent large construction projects. We can quantify and measure water as we do for dry aggregates, and the logistics to source and store it must have been taken into account in every construction project. We should be able to factor this in, especially in the construction of new cities, when the water supply infrastructure was not yet in place. Attention to water sourcing, supply, and storage can now be included in future studies of the economics of ancient construction.

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Supplementary Material

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Archéologie expérimentale et volume d'eau utilisé dans les mortiers hydrophobes romains (*opus signinum*)

L'opus signinum *est un mélange de mortier de chaux incorporant de la céramique concassée servant d'agrégat. Étant étanche, on l'a utilisé pour revêtir des structures telles que des aqueducs et bassins. Alors qu'il existe maintes reconstitutions de « béton » romain, les revêtements hydrophobes ont peu retenu l'attention et les reconstructions préliminaires, dans l'ensemble, concernent surtout les éléments secs et la chaux plutôt que le volume d'eau nécessaire à la fabrication du mortier. L'expérience présentée ici a pour but de mieux comprendre, avec le concours de maçons traditionnels, les mélanges et l'application des revêtements hydrophobes et de calculer le volume d'eau requis par échantillon. Les données acquises permettent d'estimer la consommation en eau sur les chantiers romains et ce qu'elle représentait en termes logistiques ainsi que d'évaluer les aspects techniques de ce type d'enduit.* Translation by Madeleine Hummler

Mots-clés: *opus signinum*, mortier de chaux, eau, archéologie expérimentale, ethnographie

Eine experimentelle Messung des Wasserverbrauchs bei römischen wasserabweisenden Mörteln (*opus signinum*)

Opus signinum *ist eine Kalkmörtel-Mischung mit Schamotte als Zuschlagstoff. Da der Mörtel wasserfest ist, wurde er für die Abdichtung von Strukturen wie Wasserbecken und Aquädukten benutzt. Obwohl man römischen „Beton" in mehreren Rekonstruktionen wiederhergestellt hat, gibt es nur wenige Untersuchungen von wasserabweisenden Auskleidungen und diese haben sich auf die Trockenkomponenten und den Kalk und nicht auf den Wasserbedarf des Mörtels konzentriert. Das Ziel des vorliegenden Experiments war, mithilfe von erfahrenen traditionellen Baumeistern, die Mischungen und Anwendungen von wasserfesten Beschichtungen besser zu verstehen und den Wasserbedarf von einzelnen Proben zu messen. Die Ergebnisse tragen zur Auswertung des Wasserverbrauchs und der damit verbundenen Versorgung auf römischen Baustellen bei und vermitteln aufschlussreiche Einblicke in den technischen Aspekten dieser spezifischen Art von Bekleidung.* Translation by Madeleine Hummler

Stichworte: *opus signinum*, Kalkmörtel, Wasser, experimentelle Archäologie, Ethnografie