ESTUDIOS / *STUDIES*

Water consumption in Roman lime mortar construction: a calculating method

El consumo de agua en la construcción romana con morteros de cal: un método de cálculo

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ABSTRACT

Roman concrete is one of the areas of Ancient construction which has drawn the most attention. Many studies have been devoted to the technical and chemical properties of concrete and the economics of the Roman construction industry. In these studies, the role of water is always acknowledged as very important and it is usually indicated that water was consumed in large quantities. And while many calculations of the number of man-hours, lime, stone, timber, and other materials have been done, there has been no approach to calculate the necessary volume of water. In this paper, I propose a set of proportions, derived from written sources, modern recommendations, and scientific analyses which are contrasted with experimental results, from which to derive an approximation of the volume of water that was necessary in Ancient Roman mortar construction. This will be a helpful calculation method for future studies on ancient building economics and the practicalities of mortar construction.

Key words: Ancient construction; lime mortar; Roman concrete; economics of construction; water consumption.

RESUMEN

Los hormigones romanos son una de las áreas de la construcción en la Antigüedad que han atraído más atención. Muchos estudios se han dedicado a las propiedades técnicas y químicas de este hormigón y a la economía de la industria de la construcción romana. En estos estudios, siempre se señala el papel del agua como importante y se indica que se consumía en grandes cantidades. Y aunque se han realizado cálculos para determinar las cantidades de horas de trabajo, de cal, piedra, madera y otros materiales, no ha habido estudios semejantes para calcular los volúmenes de agua necesarios. En este artículo, propongo una serie de ratios –derivadas de las fuentes escritas, recomendaciones modernas y análisis científicos, contrastadas con resultados experimentales– con las cuales llegar a una aproximación a los volúmenes de agua necesarios en las construcciones en mortero romanas. Esto será una útil estimación para futuros estudios sobre las practicidades y las economías de la construcción en mortero en la Antigüedad.

Palabras clave: construcción en la Antigüedad; mortero de cal; hormigón romano; economía de la construcción; consumo de agua.

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INTRODUCTION

Since Janet DeLaine published her thesis on the Baths of Caracalla (DeLaine 1997), there has been an increasing interest in the economics of ancient construction. While the foundations of the study were set by Choisy in the 19th century, it has been in the last thirty years that the field has developed into a study of how the consumption patterns of materials and labour necessary in large construction projects had an impact on the Roman imperial economy (Camporeale 2010; DeLaine 2017; Goldsworthy and Zhu 2009). Most of these studies, however, have not discussed water consumption as part of the building cycle besides briefly acknowledging that it was necessary for construction. Behind this lack of specificity lie three problems. The first is an economic issue: prima facie, water could be available for free, leading to the assumption that water was not likely to have had a major economic impact on the project's budget. A second would be an engineering problem: there have been no attempts to measure water to mortar ratios because many variables (from the type of sand to the weather at the time of construction) have an impact on the volume of water needed to carry out a construction project, making it difficult achieve an accurate solution (Brune 2010: 18, 330). The third one is the scale of the constructions: small plastering operations could have been done by transporting from a workshop required amounts of pre-mixed materials, but large construction sites would have needed mixers constantly on-site.

However, water is too essential in construction sites to dismiss it. Water is not only needed for mixing mortar; it is needed for several daily, mundane activities like drinking, cleaning, or soaking the handles of loose tools. Nowadays water is also needed for dust suppression, but in Antiquity, it would have been necessary to wet ropes and cool down pulleys. Water itself may have had only a minute impact on the overall budget, but it was indispensable all the same. Moreover, because of its physical properties, water cannot be simply piled or stacked in a corner: the logistics of sourcing and storing water required preliminary planning and on-site solutions that could range from wells to cisterns or from aqueducts to water carriers. Archaeologically, these solutions may have been ephemeral or invisible, but they may also offer possible explanations for short-lived features found under or around other elements. Snyder (2020) has calculated that each cubic metre of slaked lime required 1 person-hour of water collecting, and another 1 person-hour was needed for every cubic metre of freshly mixed mortar. These calculations are a useful starting point to think about how a site was managed, but without knowing how much water was needed on site, it is impossible to begin to address the issues of sourcing and storing or to get an overall picture of the workings of a construction site.

In this paper, I want to put forward a tentative calculation method to estimate how much water was necessary for lime-based constructions in the Roman period, although the same model can be applied to other historical periods where lime mortar (with and without pozzolanic additions) was used. The initial premise is that we know from written sources, archaeological analyses, and ethnographic comparanda how lime-based mortars were mixed in the Roman period. These mixes required variable quantities of water at different stages, and these quantities can be calculated (when they are fixed) or estimated (when they are variable). Since it is possible to calculate the minimal stoichiometric and volumetric relationships between the original components and the final volume of mortar, it is possible to calculate the minimum necessary water input. It is from these calculations that we can begin to think about the logistics of securing water for construction sites. These theoretical calculations will not give absolute or precise results; these are approximations that will only provide a lower estimate for the ratio between the volume of concrete masonry and the original water input. The fact that these calculations are based on broad theoretical models rather than precise measurements specific for each individual monument does not undermine their value or usefulness, and they can be the stepping stone for further research (cf. Martínez Jiménez 2020).

With this in mind, the paper is structured in four parts: first, a brief definition of the terms used in the archaeological literature and the rest of the paper; second, a schematic overview of the mortar mixing process, noting the various moments in which water is added to the mix; third, the main body of calculations, resulting in a series of broad ranges for water inputs at the different stages of the *chaîne opératoire*; and fourth, the application of these calculations the construction of the sixth-century Reccopolis aqueduct to illustrate the practical validity of this method.

## I. MORTARS, CONCRETE, AND *OPERA*

Before the invention of quick cements of the Portland type, most construction used lime mortars as a binding agent. In Antiquity, these were overwhelmingly aerial

limes; that is, non-hydraulic limes that dried in contact with air. In this sense, a lime mortar is a cementitious substance resulting from the mixing of lime with an inert aggregate (usually sand) that adds volume and stiffness while preventing shrinkage. This mix solidifies with time and binds together whatever building materials (bricks, rubble, stone) it has been applied to.

The scientific explanation for this process is the sequence of chemical reactions known as the lime cycle (Hobbs and Siddall 2010; Wright 2005: 174-176). Limestone, which is mostly calcium carbonate ($CaCO_3$), is calcined in large furnaces, expelling its carbon dioxide component while oxidising the calcium, resulting in calcium oxide (CaO). Calcium oxide is also known as quicklime.

$$CaCO_3 \rightarrow CaO + CO_2$$
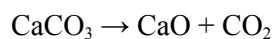
Quicklime reacts violently with water in a very exothermic reaction (15,500 cal/mole). This process (known as 'slaking') turns quicklime into slaked lime or calcium hydroxide.

$$CaO + H_2O \rightarrow Ca(OH)_2$$
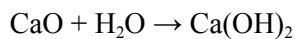
Calcium hydroxide is a powder, but the slaking process is done with extra water so that the result is creamy paste or putty. In aerobic circumstances, slaked lime slowly dries and exchanges the hydrogen and oxygen it contains for carbon from the air, liberating water as vapour and carbonising back to calcium carbonate.

$$Ca(OH)_2 \text{ (aq)} + CO_2 \rightarrow CaCO_2 + H_2O \text{ (g)}$$
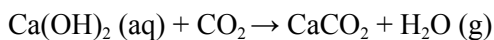
Lime (quicklime/slacked lime) is, therefore, the reactive component in these mixes. However, (slaked) lime on its own forms a yoghurt-like paste; for it to be usable in construction it needs sand to give it consistency (Oleson 2010). Therefore, even if these mixes are mostly composed of sand, they are still referred to in the literature as 'lime mortars'. This is also a way of differentiating them from other building binders identified in the archaeological record, like clay mortars. This type of binder that combines lime with inert, sandy aggregates has been in use for centuries, before and after the Romans (Adam 1994 [1989]: 65ff; Bonen *et al*. 1994; Wright 2005: 146-189), whereas the Romans developed new lime-based mortars by adding reactive aggregates, revolutionising lime construction.

In the third century BC, builders in central and southern Italy noticed how the addition of some local sands to their mortar mixes improved the final result. The volcanic nature of these sands (*pozzolana*) chemically modified the lime cycle, giving the mix hydraulic properties and allowing it to solidify underwater (Adam 1994 [1989]). Later on, it was noticed how the addition of crushed pottery sherds (chamotte) had similar results.[2] This new Roman type of pozzolanic mix was, during the following two/three centuries, used alongside newly-developed building techniques, which included the use of standardised, pre-cut conical/pyramidal stones, a large-scale brick production, the use of coffering to frame and shape mortar bound with rubble (*caementa*, from where we get 'cement' and its cognates), and even the use of different types of rubble with different weights to improve vaulting techniques (Mogetta 2013; Sear 2008 [1982]: 124-132). This was the beginning of an architectural revolution which continued to develop in the early Empire with further experimentation with vaulting and doming, and new materials (Lancaster 2005; Van Oyen 2017; Lechtman and Hobbs 1987).

Lime-based mortars and associated Roman techniques are found across the empire. In Roman foundations and pre-existing cities alike, *opus caementicium* was used as the structural core of large buildings that were then faced with brickwork and stonework (Fig. 1). Many of these facings, which were also bound with mortar, are known in the archaeological literature through Latin names. Some appear in Vitruvius (like *opus incertum*, *reticulatum*) while others (like *opus signinum, latericium,* and *vittatum*) are inaccurate archaeological shorthand attributions (Gros 2013; Sear 2008 [1982]; Rubio Bardon 2011). Mosaic floors were embedded into a bed of *opus signinum*, the same material that was used to line cisterns, vats, pools, and the conduits of aqueducts. Most studies of Roman concrete—whether replications, compositional analyses, or mechanic and structural tests— have focused specifically on those with pozzolanic additions (Brune 2010; Goldsworthy and Zhu 2009; Oleson *et al*. 2004; Sánchez Moral *et al*. 2005; UNILAD 2021), but pozzolanic mortars did not replace lime-and-sand mortars. Only in a few special cases were

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[2] Chemically, if ceramics that have been fired to 900°C or less are added to the lime, then the resulting mortar obtains pozzolanic properties, including hardening under water (Hobbs and Siddall 2010). However, the Romans used all sorts of ceramics, including those fired at higher temperatures, like Samian ware.

Figure 1. Superimposed layers of mortared rubble as the structural core *(opus caementicium)* of the theatre of Augusta Emerita (Mérida, Spain). Image by the author.

volcanic sands exported beyond Italy, as in the harbour of Caesarea Maritima (Hohfelder *et al*. 2007); more often, local materials were sourced, so that even if across the empire Roman concrete techniques were employed, they did not all use pozzolanic mortars as they did in Rome and Italy (Dix 1982; Uğurlu Sağın *et al*. 2021).

II. LIME MORTAR BUILDING: WATER IN THE *CHAÎNE OPÉRATOIRE*

As outlined above, building with lime mortar was a process that consumed water at different stages of the mortar-making process. We must remember that not two mortars were the same and that there was not one single way of mixing it, as the purpose of the mortar dictated the proportions, types, quantities, and qualities of the components (of limes and aggregates alike). It was not the same to prepare a mix for building foundations as it was to make a mix for a final plastering operation, and

this had an impact on the water needs on construction sites. Despite this, the mortar mixing and building sequence followed this overall *chaîne opératoire*.

Nowadays, as in Antiquity, the first stage in the preparation of any lime-based mortar is to slake the quicklime. Slaking is only the process of mixing quicklime (which comes in rocks and nuggets out of the kiln, although it can be crushed into a powder) with water, which chemically results in portlandite powder (calcium hydroxide); as mentioned before, this was usually combined in one single process with the making of a paste, by adding extra water in a volumetric ratio of 1:3 quicklime to water. Dix (1982: 338) describes how slaking was done by filling a pit with a foot of water and then adding quicklime until half full with lime, which was then mixed with a hoe while adding extra water. Such pits, lined with timber, have been found in Verulamium and Wroxeter (Morgan 1992: 9, 16), and may relate to the ones described by Vitruvius in which the lime would slake over time (*calx in lacu macerata*: Vitr. 7.2.2). The

resulting slaked lime paste needed to mature so that any remaining particles of quicklime would be slaked. The longer the paste matured, the fewer of these unslaked particles there would be, and the better the final result was. This could take up to three years, resulting in a very sought-after vintage lime (Pliny, *NH* 36.55).

Depending on the nature of the construction, the lime could be slaked in pits or vats on site, maturing overnight (or longer) if necessary. Quicklime is much lighter than limestone, making it easy to transport in bulk, a solution perhaps more suited for larger projects, but the rocks need to be transported in such a way that they do not slake in contact with the humidity in the air. From Pompeii, however, we know that the slaking could have been done directly at the lime burners or at a builder's yard because pre-slaked lime paste was transported to the site in amphorae, as we see in the Casa della Soffita (V.3.4). This would be an ideal solution for smaller works (Adam 1994 [1989]: 164-165; Berry 1997).

The lime paste or putty is then mixed with the aggregates, which as mentioned, adds volume and consistency to the mortar. The fact that the aggregates are mixed with pre-slaked lime is specifically mentioned in sources such as Vitruvius (2.5.1: *cum ea erit* extincta, *tunc materia ita misceatur*), Cetius Faventius (4: *calcis proxime* extinctae *duae partes ad quinque harenae mortario misceatur*), and the Wall law of Puteoli (the '*lex parieti faciendo*', *CIL* X.1781: *in terra calcis* restinctae *partem quartam indito*). In this process, the dry aggregates (sand, pozzolana, chamotte) would have absorbed some humidity from the paste because of their intrinsic physical properties. To correct the rheology of the mix (to make it less stiff and more workable and malleable), a small amount of water was added, but never enough to make it runny like modern concrete. More water never makes more mortar (Gárate 2002: 99).

At this point, it should be noted that there was an alternative way of mixing the lime and the aggregates, called 'hot mortar' or 'dry slaking' mixing. In this type of mixing, a heap of sand is formed, and the centre is hollowed out. That cavity is filled with quicklime and water is added to it. The lime slakes in the 'volcano', the crater of which is then covered in wet sand to seal the slaking chamber. After the lime has slaked, it is then all mixed to create a ready-to-use mortar which would have been good enough for structural binding and foundations. This is a method favoured by current 'traditional' masons (Lynch 2017; Adam 1994 [1989]: 164) and it was also typical in late Antiquity (Snyder 2020), because

the seal retains the heat generated during the slaking process and this accelerates and homogenises the slaking. A mosaic in the Bardo museum, depicting two workmen making mortar by pouring water from an amphora onto a pile of sandy material, illustrates this form of volcano slaking in a Roman context. Similarly, at the Casa del Sacello Iliaco (I.6.4) in Pompeii, lumps of quicklime were stacked in preparation for on-site slaking, most likely in a 'volcano' (Lancaster 2005: fig. 41).

After mixing and before application, the mortar would be left to settle (Gárate 2002: 166; Cazalla Vázquez 2002: 38). It is possible to let it unused for a while (at least in the case of non-pozzolanic mortars). Even overnight, these mortars may stiffen without properly or fully carbonising, but, if so, adding water makes the mix workable again.

Once the mortar was mixed (regardless of the method), it had to be applied to the elements that would give solidity and volume to the construction, because the mortar itself cannot be used for that purpose. This could be done by either mixing it with rubble/*caementa* when making structural cores of concrete (*opus caementicium*) or it could be applied with a trowel to the building materials (bricks, tiles, ashlar blocks). Even if these large solids fulfil different structural purposes, from a water-consumption perspective these needed to be sufficiently humid, lest they absorbed too much moisture from the mortar, causing it to shrink, crack, and dry unevenly. Therefore, building blocks or rubble would be soaked to the point of saturation and then left to dry to a point the builders and masons considered sufficient.

Even after the structure has been built, there was another phase of water consumption. As the mortar dries and carbonises, it is necessary to keep sprinkling it with water to ensure a homogenous process to prevent shrinkage and cracking. This process of soaking and hydrating is especially necessary when ambient temperatures reach 30°C (Gárate 2002: 99), an eventuality that concerns most of the Roman world for half of the year. Together with sprinkling walls and structures, it was possible to keep constructions from heating too much and drying too quickly by covering them with canvases or tarpaulins that would protect them from direct sunlight.

A last, optional step that was not always done, and that could be seen as a different process altogether, would be limewashing. Limewashing (or whitewashing) is a way of protecting walls by applying a very diluted solution of lime, usually applied on external walls to add extra protection from the elements. It is long-lasting and

it can be applied either unchanged (white) or coloured by the addition of pigments. While limewashing is not a necessary step in historical constructions, it was a usual addition in Roman building (Hughes *et al*. 2007).

III. CALCULATING WATER VOLUMETRIC PROPORTIONS

The opening premise that water is necessary on construction sites has thus been demonstrated. The sequence listed above has focused only on those processes that relate to mortar production, ignoring any other process already mentioned or not (cleaning/washing, dampening ropes and pulleys, on-site metalworking, etc.) so while the mortar was the main consumer of water on-site, it was not the only one.

The *chaîne opératoire* described above gives us the main steps from which we can begin to calculate the relationships between archaeological mortar and water input. The sequence can be summarised as follows:

$$A = S + R + W + C + D \, (+ P)$$

Where A is the total water input, S is the water consumed in the slaking process, R is the water used in the mixing of the mortar to hydrate the mix and correct the rheology, W is the potential water addition to re-work a pre-mixed mortar, C is the water used to soak the *caementa* and other structural materials, and D is the sprinkle used to correct and control the drying and carbonising process. P corresponds to the water used to whitewash a surface. In this study, all of these quantities of water will be considered to be volumetric. However, I will only consider in detail three of these different water inputs, the three that can be practicably calculated and which are also those that would have been proportionately the largest: S, R, and C, i.e. the water for the slaking, the hydration of the mortar mix, and the soaking of the rubble and structural materials.

Since these water inputs represent different stages of the *chaîne opératoire*, the relationships that can be calculated are those between the water input and intermediate results. S is calculated from the input of quicklime (V_{ql}) and the final slaked lime paste (V_{slp}). R is calculated based on the relationships between the volume of paste (V_{slp}), the volume of aggregates (V_{agg}), and the volume of the pre-hydration, 'initial' mortar mix (V_{im}). All these can, in any case, be related to the final volume of fresh

mortar (M_f) that was used in a given construction. The volume of fresh mortar is directly related to that of dry, archaeological mortar (M_d). C is independent of the volume of mortar, as it depends entirely on the volume of building materials (V_{bm}) and the volume of the structure (V_s), which can be calculated from the archaeological remains. The wall area to be whitewashed (a_{ww}) is unrelated to this process, but its surface is an amount calculated from the reconstructed volume of the structure.

$$V_{ql} \rightarrow V_{slp} \rightarrow V_{agg} \rightarrow V_{im} \rightarrow M_f \rightarrow M_d \rightarrow V_{bm} \rightarrow V_s \, (\rightarrow a_{ww})$$

Because the real or reconstructed archaeological remains (V_s) are the point of reference, it is necessary to calculate backwards in the sequence of events and the *chaîne opératoire* to obtain a volumetric relationship between it and the earlier intermediate products (Tab. 1).

Table 1. Summary table explaining the meanings of the abbreviations for quantities and volumes used in the calculations and equations in the text.

Abbrev.	Meaning	Abbrev.	Meaning
A	Total water input	V_{slp}	Volume of slaked lime paste
S	Slaking water input	V_{agg}	Volume of dry aggregates
R	Rheologic (stiffness) input	V_{im}	Volume of the initial mortar mix
W	Re-working input	M_f	Volume of fresh mortar
C	Water used to soak materials	M_d	Volume of dry mortar
D	Water used to regulate pace of drying	V_{bm}	Volume of building materials
P	Whitewash input	V_s	Volume of the mortared structure
V_{ql}	Volume of quicklime	a_{ww}	Area to be whitewashed

A) Intermediate calculations

Built volume to mortar and building material ratio

For any given structure and its reconstructed volume (V_s), it is possible to calculate which percentage of it corresponds to mortar and which to building materials.

$$V_s = M_d + V_{bm}$$

The rubble/block to mortar ratio that rules the relationship between V_s and M_d depends entirely on each construction's needs. In cores of *opus caementicium*, the proportion between mortar and rubble would have been different than in brick constructions; in a reconstructed *pila* built in Brindisi, Italy, the proportion of rubble and mortar appears to have been 65% rubble to 35% mortar (Oleson *et al*. 2004: 219), which is similar to the remains studied at the Piazza Dante in Rome (Serlorenzi and Camporeale 2017). Janet DeLaine (1997: 123) calculated the opposite proportion for the Baths of Caracalla. In late antique constructions in Spain (e.g. the sixth-century aqueduct of Reccopolis; Martínez Jiménez 2015) the proportion seems closer to 70% rubble to 30% mortar. A modern brick wall (using the walls of the Cambridge Classics Faculty as an example, which has no concrete core) consists roughly of 60% bricks and 40% cement, with partly-hollow bricks.

These empirically-calculated proportions can be expressed mathematically with two variables: α as the volumetric percentage of building material and β as the percentage of mortar. With those, it is possible to explain the relationship between the archaeological remains and the original volumes of mortar and building materials:

$$\alpha + \beta = 1$$
$$V_{bm} = V_s \times \alpha$$
$$M_d = V_s \times \beta$$

For the examples above, α and β would be 0.65 and 0.35 in the Brindisi *pila*, and 0.7 and 0.3 in the Reccopolis aqueduct. In the case of *opus signinum* linings, where the mortar is applied as a layer and not as a binder, β is 1, since there are no building blocks to consider.

Dry (archaeological) mortar to fresh mortar ratio

Going one step further up in the process, we should consider the shrinkage in the volume of fresh mortar (M_f) as it carbonises and dries (M_d). Measurements have shown how this shrinkage is minimal, but not negligible: a maximum of 7‰ in volume (Pozo Antonio 2015; Sánchez *et al*. 1997; cf. Cazalla Vázquez 2002: 138-143). Considering this, the volume of fresh mortar will be the 993‰ of the proportion defined by β:

$$M_f = M_d \times 993/1000 = V_s \times \beta \times 0.993$$
$$M_f = V_s \times 0.993\beta$$

Fresh mortar to paste and aggregate ratios

The volume of fresh mortar (M_f) is a fraction (γ) of the sum of the separate volumes of the initial elements (V_{im}), which are the lime paste (V_{slp}) and the aggregates (V_{agg}), plus water added to correct the rheology of the mix (R). The gamma factor is a fraction because the aggregates are dry solids that absorb humidity (i.e., the volume of water) from the paste as it is mixed and compressed, and while the mass remains constant, the volume does not (Oleson *et al*. 2004: 219; DeLaine 1997: 123).

$$V_{im} = V_{slp} + V_{agg}$$
$$M_f = V_{im} \times \gamma + R$$

This overall shrinkage of the mix depends on the absorptive qualities of the aggregates (Dapena García 2009; Jackson *et al*. 2009: 2483), the evaporation of pockets of air, and the filling of pores (Tab. 2). The Romans were fully aware of these physical properties (Vitr. 2.4, 2.5, 2.8.2).[3]

Table 2. Average densities and absorption rates of common aggregates used in Roman mortar mixing.

	Density (kg/m³) (average)	Absorption (%wt)	Kg of water per saturated m³
Pozzolanas	1370	10-30	137-411
Sand	1550	0.8-6	12.4-93
Chamotte	1075	29-36	311.75-387

Considering these absorption rates, γ can have varying values depending on the composition of the mortar. There is no single way of making lime mortars, and mortar 'recipes' could vary greatly depending on the purpose of the mortar, the type of aggregates, and even the time of the year. It is difficult to theorise about a single type of lime-based mortar, even if the 1:3 lime to sand ratio was the most basic mix in Roman times (Lancaster 2005: 54-55; Siddall 2010: 166). "Fattier" mortars have higher lime contents, and "slimmer" ones less. Latin sources (Cato, *Rust*. 15.1; Vitr. 2.5.5-7; Pliny, *NH* 36.175; Faven-

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[3] This ratio and the density have been experimentally calculated for this purpose at the archaeometry laboratory of the Department of Prehistory and Archaeology of the University of Granada.

tius, 4; *CIL* X.1781) give indications of various proportions (volumetric, measured in *modii*) of slaked lime to sand and other aggregates like crushed pottery which range from 1:2, 2:5, and even 1:4. Scientific analyses carried out on historical mortars and modern attempts at recreating Roman-like concrete structures show that this range of proportions was indeed used (Brune 2010; Oleson *et al*. 2004; Jackson *et al*. 2009). From analyses conducted on *opera signina* from Corinth, we know that the proportion of lime paste to crushed pottery is between 1:2 and 1:3 (Siddall 2010: 166). Ethnographic comparanda further confirm that 1:3 is the most common mix and that anything beyond 1:4 is unworkable and unsafe (Gárate 2002; Lynch 2017; cf. Oleson 2010). A quick calculation based on how much moisture is absorbed by each aggregate depending on the mixing proportions can give us an estimate for γ (Tab. 3).

Table 3. Gamma ratio: volumetric relationship between the volume of fresh mortar *(M_f)* and the sum of the volumes of the different components. Because of the dry, porous nature of the aggregates (sand, chamotte, pozzolana), these absorb moisture from the paste and part of the rheologic water (*R*), thus resulting in a volume reduction.

Mortar type	γ
Pottery + sand *opus signinum*	0.6-0.7
No-sand *opus signinum*	0.5-0.6
1:3 sandy mortar	0.75-0.85
Pozzolanic mortar	0.6-0.7

The different mixing proportions can also be expressed as volumetric relationships that give us an approximation to the ratio between the originally added paste (V_{slp}) and the final volume of mortar (M_f). Considering that the aggregates (V_{agg}) are always added in a quantity directly proportional to the paste (δ) and that the ratio always ranges between 2 and 4, we can propose this:

$$V_{agg} = \delta \times V_{slp}$$
$$2 \leq \delta \leq 4$$

If we take into account the previous relations, we can deduce the volumetric correspondence between the original paste input and the archaeological remains:

$$M_f = V_{im} \times \gamma + R$$
$$= (V_{slp} + \delta \times V_{slp}) \times \gamma + R$$
$$= V_{slp} \times (1 + \delta) \times \gamma + R$$

$$V_{slp} = (M_f - R) \div (\gamma + \delta\gamma)$$
$$= (V_s \times 0.993\beta - R) \div (\gamma + \delta\gamma)$$

This last equation still depends on one factor (*R*), a quantity of water for which we do not have a known value yet, but that I will further explain in the next section.

B) Water-related calculations

Water for the structural building materials (C)

The most straightforward calculation is the one for *C*, with which there is a direct relationship with the archaeological starting point, V_s.

As explained above, *C* is the amount of water used to keep the structural materials (the building blocks) humid to prompt a homogeneous drying while avoiding that these absorb too much moisture from the mortar (Fig. 2). In this sense, the first thing that needs to be considered is the absorptive capabilities of the building materials, which as dry, earthy solids will absorb water depending on their surface porosity. The second is the proportion between structural materials and the binding mortar. Both are globally extremely variable, but they are site-specific; this is to say, that for each example of mortared construction there will be a specific building block-to-binder distribution and each building material has a specific absorption ratio.

If we take the material's absorption capabilities (ε), and as shown in table 3, there is a great degree of variability, as it depends entirely on the material's porosity (Dapena García 2009; Oguz *et al*. 2014; Jackson and Marra 2006; Jackson *et al*. 2009; Pötzl *et al*. 2022). Granite and marble absorb very little water, while porous stones and brick have higher absorptive capacities. In this case, ε is the maximum percentage of water that can be absorbed per volume of solid in kiln-dry circumstances (Tab. 4).

Depending on the building material, ε gives a maximum value of water absorbed, although it is unlikely that all the bricks/blocks were soaked to the point of saturation. This value, however, represents the maximum amount of water needed to keep the building materials humid.

$$C = V_{bm} \times \varepsilon$$

Figure 2. Water applied to 'rustic' brick before they are plastered with *opus signinum,* during the 2021 *opus signinum* recreations of the AQUAROLE project, at the Lime Museum of Morón (Seville). Image by the author.

Table 4. Average densities and absorption rates of common *caementa* used in Roman concrete constructions, including their calculated ε ratio.

	Density (kg/m³)	Absorption (%wt)	Kg of water per saturated m³	ε (vol. absorbed water ratio)
Granite	2560	0.4	10	0.01
Sandstone	2160-2560	1-20	21.6-512	0.021-0.512
Limestone	1760-2560	3-12	158.4-307	0.158-0.307
Marble	2300-2800	0.2	4.6-5.6	0.005-0.006
Brick	1500-1800	10-20	150-360	0.15-0.36
Volcanic tuff	1500-1700	10-40	150-680	0.15-0.68
Pumice	800	50	400	0.4

If we put this together with the calculations from the previous section, we get:

$$C = V_s \times \alpha \times \varepsilon$$

This means that a brick wall ($\varepsilon = 0.36$) 2m high, 0.5m wide, and 10m long ($V_s = 10m^3$) with a 70:30 brick to mortar ratio ($\alpha = 0.3$) would have needed a maximum of $1.08m^3$ of water to moisten the bricks ($\approx$10% of the wall's volume).

Water for the mortar mix (R)

In Antiquity, as today, it was very difficult to judge how much water needed to be added to a mortar mix, as it really depended on the purpose of the mortar, the humidity retained by the aggregates, and the environmental circumstances (Fig. 3). For our study, we want to relate this amount of water (R) as a volumetric proportion (ζ) to the initial mortar mix (V_{im}), so that:

$$R = V_{im} \times \zeta$$

R or the rheologic water can be approximately defined in several ways. Brune (2010: 338-42) suggests a mass ratio of aggregate to the water of 1:0.15, which was specific for his experimental reconstruction, although it is possible with his published data (Brune 2010: table 9.3) to obtain a mortar mix to water volumetric ratio which, in this case, coincides numerically with the weight ratio between water and aggregate (1:0.152). Brune's mix is probably as dry as a mix could get, since it is described repeatedly as 'stiff'. Cazalla suggested a 1:1 lime paste to added water weight ratio, (Cazalla Vázquez 2002: 58-61, table 17). The

Figure 3. Water added to a mortar mix. Photo taken during the 2021 *opus signinum* recreations of the AQUAROLE project, at the Lime Museum of Morón (Seville). Image by the author.

volumetric relationship here is 1:0.31. Another ratio can be taken from Samuelli Ferretti's results, who calculated in his experiments a volumetric proportion between hydrated lime and water of 1.39:1, which is to say 1:0.719 (Brune *et al.* 2010: 41). This, considering the aggregate to paste ratios (in his case $\delta = 3$, so $V_{im} = 4$), gives a much higher mix to water ratio (1:0.347). Adam (1994 [1989]: 74), more helpfully, suggests the addition of water be between 15% and 20% of the volume of the mix (so, between 1:0.15 and 1:0.2). From these overall approaches we can conclude that the water input during the mortar mixing stage is broader than Adam's proposal, giving us a value for (ζ):

$$0.15 \le \zeta \le 0.35$$

Linking this relationship between the initial mortar mix and the final volume (V_s), we need to use the previously calculated equations:

$$V_{im} = R \div \zeta \text{ and } V_{im} = (M_f - R) \div \gamma \rightarrow R \div \zeta = (M_f - R) \div \gamma$$
$$R = M_f \times \zeta \div (\gamma + \zeta)$$

$$\underline{R = V_s \times 0.993\beta \times \zeta \div (\gamma + \zeta)}$$

With this, it is also possible to calculate the direct relationship between the volume of paste (V_{slp}) and that of the structure (V_s):

$$V_{slp} = (V_s \times 0.993\beta - R) \div (\gamma + \delta\gamma)$$
$$= \{V_s \times 0.993\beta - [V_s \times 0.993\beta \times \zeta \div (\gamma + \zeta)]\} \div (\gamma + \delta\gamma)$$
$$= [V_s \times 0.993\beta \times (\gamma + \zeta) - V_s \times 0.993\beta \times \zeta] \div [(\gamma + \zeta) \times (\gamma + \delta\gamma)]$$
$$= (V_s \times 0.993\beta \times \gamma) \div (\gamma^2 + \delta\gamma^2 + \zeta\gamma + \delta\zeta\gamma)$$

$$\underline{V_{slp} = (V_s \times 0.993\beta) \div (\gamma + \delta\gamma + \zeta + \delta\zeta)}$$

Returning to our theoretical example of the ten-metre brick wall ($V_s = 10m^3$), we need the mortar ratio ($\beta = 0.7$) and the rheologic water ratio (ζ), which ranges between 0.15 and 0.35. Since we are assuming a 'standard' sandy mortar, the shrinkage of the mortar mix (γ) could vary between 0.75 and 0.85. If we take into consideration the different possible values for γ and ζ, we obtain for R a value ranging between 1.16 and 2.03m³ ($\approx$10-20% of the wall's volume).

Slaking water (S)

The water needed to slake the lime can be more easily calculated. Stoichiometrically, each mole of calcium oxide

requires one mole of water to be slaked into hydroxide. Calcium hydroxide (portlandite) is a powder nowadays used in mortar construction, but that does not appear to have been used in Antiquity, where quicklime (V_{ql}) was slaked with extra water (S) to create a paste (V_{slp}).

$$V_{ql} + S \rightarrow V_{slp}$$
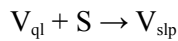
The ratio between quicklime and water varies depending on the needs of the mortar and the chemical composition of the original limestone (Fig. 4). The slaking ratio (η) is traditionally considered to be 1:3 in volume, but it could go up to 1:4, as it depends on the calcium content of the original limestone, the thoroughness of the burning, and any residual impurities (Harper 1934; Goldsworthy and Zhu 2009: 936-937; Lancaster 2005: 51). In his experimental reconstruction, Brune slaked it at a weight ratio of 1:2.1, which becomes a 1:1.85 volume ratio using the densities provided (Brune 2010: 336-342), in turn resulting in a "stiff but malleable paste" as opposed to the creamy, yoghurt-like texture of other matured limes (Gárate 2002; Cazalla Vázquez 2002: 87-88). We can express these data as follows:

$$V_{ql} + S \rightarrow V_{slp}$$
$$S = \eta \times V_{ql}$$
$$1.85 \leq \eta \leq 4$$

Insufficient water during the slaking process, moreover, can lead to uneven slaking and the presence of unslaked

Figure 4. Lime slaking: lime putty after the addition of water to nuggets of calcined limestone (quicklime). Photo taken during the 2021 *opus signinum* recreations of the AQUAROLE project, at the Lime Museum of Morón (Seville). Image by the author.

nodules in the paste. These nodules can become encased in a film of slaked lime, but they can come into contact with water at later stages when the paste is mixed with aggregates and more water — if these nodules slake in the mortar they will expand in volume, release energy, and prompt fractures in the drying mortar (Cazalla Vázquez 2002).

Slaked lime has a different chemical configuration than quicklime, and when it becomes a paste this results in an expansion in volume (θ). This volume of paste can be between 2.5 and 4 times the original amount of lime (Lancaster 2005: 53). Brune's experiment (2010: 336, note 32) confirms the volume expansion from quicklime to the paste (obtaining, in that case, a 285% volume increase as compared to the initial amount of bulk quicklime).

$$V_{slp} = \theta \times V_{ql}$$
$$2.5 \leq \theta \leq 4$$

With this, it is already possible to calculate the theoretical water input needed to slake quicklime and to create a lime paste.

$$V_{ql} = S \div \eta \text{ and } V_{ql} = V_{slp} \div \theta$$
$$S = (\eta \div \theta) \times V_{slp}$$

Taking into consideration the range of values for both the water to quicklime ($1.85 \leq \eta \leq 4$) and the quicklime to paste ($2.5 \leq \theta \leq 4$) ratios we can obtain results that go from 46 to 160% of water content in the paste, which is of course, an impossibly wide range. Chemical analyses show that water content in lime paste decreases as it matures, but it ranges between 45-70% (Margalha *et al*. 2013; Cazalla Vázquez 2002: 47-48). The excessive percentage of water obtained in these calculations can be accounted for in three ways: improbable mixes, water lost to evaporation during slaking, and/or water 'exuded' by the paste as it matures. Having said this, to calculate water inputs during the process of slaking, we can accept and use these values derived from η and θ as maximums and minimums.

Lastly, we can use this calculation for water input (S) as it relates to the volume of paste (V_{slp}) with the previous equations to link this volume of water to the overall structure (V_s):

$$S = (\eta \div \theta) \times V_{slp}$$
$$= (\eta \div \theta) \times [(V_s \times 0.993\beta) \div (\gamma + \delta\gamma + \zeta + \delta\zeta)]$$

$$\underline{S = (V_s \times 0.993\beta\eta) \div [\theta \times (\gamma + \delta\gamma + \zeta + \delta\zeta)]}$$

Naturally, with these same calculations we can estimate the amount of quicklime (V_{ql}) needed for any given construction:

$$V_{ql} = V_{slp} \div \theta$$
$$V_{ql} = (V_s \times 0.993\beta) \div [\theta \times (\gamma + \delta\gamma + \zeta + \delta\zeta)]$$

As before, we can take the brick wall example ($V_s = 10m^3$). For it we have the mortar ratio ($\beta = 0.7$), a range of values for the slaking water ($1.85 \leq \eta \leq 4$), for the expansion of the paste ($2.5 \leq \theta \leq 4$), and all the other variables (γ, δ, ζ). The results of this calculation vary within a broader range, in this case between 0.57 and 3.22m³, which is to say roughly 6 to 32% of the volume of the wall. The wall would also have required 0.14-1.74m³ of quicklime ($\approx$125.4-271.1kg).[4]

Whitewashing (P)

Whitewash is a very diluted lime, where the quicklime is slaked in a proportion of 1:5 rather than 1:3. Modern and ancient reconstructed recommendations for lime washing (Adam 1994 [1989]: 73; Harper 1934; Mold and Godbey 2005) state that the proportion (ι) of quicklime to water in whitewash (V_{ww}) ranges between 70% and 80%, sometimes even 85%.

$$P = \iota \times V_{ww}$$
$$0.7 \leq \iota \leq 0.85$$

The relationship between the necessary volume of whitewash and the area to cover is easy to determine. Modern standards suggest using a 15l drum to whitewash a surface of 25-30m³. This means that 1m³ is good enough for 2000m². With this, it is possible to calculate the relationship between P and the painted area (a_{ww}).

$$2000 \times V_{ww} \rightarrow a_{ww}$$
$$P = a_{ww} \times \iota \div 2000$$

If we were to whitewash the brick wall from our example, we would need 10l of limewash per side, which would contain between 7 and 8.5l of water (0.007-0.0085m³).

C) Discussion

The simple example that has been used to illustrate these calculations shows the possibilities and disadvantages of these calculations. First of all, we can estimate that between 2.7 and 6.3m³ of water were necessary to build a 10m³ brick wall. That is between 27 and 63% of the final volume of the structure, which already allows us to visualise, comparatively, how much water was needed. This is, of course, without accounting for spillage, wastage, or any other uses of water not considered in the *chaîne opératoire*. If the slaking was done on-site (either pit-slaking or a 'volcano'-type hot mortar), then a bare minimum of three thousand litres (and very probably a great deal more) would have been needed on site for our 10m long wall. If the mortar was made with pre-slaked paste, then the water needed on site decreased to 2.24-3.11m³, which still is a significant quantity for relatively small construction.

According to the most recent finds in France, Roman barrels contained between 1,000-1,200l of water (Mille and Rollet 2020); three would have sufficed for this particular building project. While barrels per se are not necessarily a useful way of measuring water transport and storage in the Roman world, it is a first step that prompts further questions. Were the barrels transported full or empty? The latter makes more sense (water is heavy), but where did the water come from otherwise? In cities, wells and public fountains are possible sources, but water would need to be carried from the source to the storage. Perhaps only one barrel was needed, but it would need regular refilling. It is not uncommon in the ethnographic record to encounter that water for mortars was stored on-site for a period of time so that any minerals dissolved in the water would 'settle down' (Gárate 2002: 99), reducing the chances of secondary salts developing in the mortar at a later stage (Cazalla Vázquez 2002: 190-199), as it carbonised. In larger and long-term construction projects, the logistics of water sourcing and storage become more complex.

This example also serves to highlight that these calculations depend on a large number of variables, which change from site to site and from mortar to mortar (Tab. 5). In some cases, a quick visual assessment may be sufficient to estimate the value of some of the variables, most likely α, β, and δ. Some others (especially γ and ε and, to a lesser extent, ζ) require further research into the physical and mechanical properties of the different solids. Roman concretes of the *opus caementicium* type in particular are very complex materials with far more complex compositions than the simplified proposal included in this study, in

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[4] Based on a bulk density of 880kg/m³ (Brune 2010).

Table 5. Table summarising the variables used for calculations in the text, with their meanings and values.

	Variable refers to	Value range	NB
α	Volumetric proportion of building blocks	0-1	$α + β = 1$
β	Volumetric proportion of mortar	0-1	$α + β = 1$
γ	Volumetric compression of mortar mix	0.5-0.85	Depends on aggregates
δ	Aggregates to paste volumetric ratio	2-4	Depends on purpose of mortar. Usual is 3.
ε	Volumetric ratio of water absorption by building blocks	0.02-0.7	Depends heavily on the material
ζ	Rheologic water to mortar mix ratio	0.15-0.35	
η	Water to quicklime vol. ratio	1.85-4	"Standard" is 3-3.5
θ	Vol. expansion ratio, quicklime to paste	2.5-4	Depends on original limestone composition and added water
ι	Proportion of water in limewash	0.7-0.85	

which different types of aggregate and *caementa* of varying properties were used in combination. The vault of the Great Hall of Trajan's market, for instance, used three different types (and sizes) of tuff and pozzolana, and the piers were made of brick-faced *opus caementicium* cores (Jackson *et al.* 2009). The calculations for these constructions will be, necessarily, more intricate.

While measurements and calculations for specific mortars will result in accurate assessments of water input for those particular building projects, it is unlikely that these will have an impact on the overall order of magnitude of the more generic calculations. In the introduction, I underlined that I propose these calculations as a guide; that this approach will give a rough framework to think about the water needs on construction sites. Of course, if a given monument needed tens (or hundreds) of cubic metres of water, this does not mean that there had to be a vat capable of holding that volume, but there must have been reliable sources and ways of storing water that could cater, on the long run, for the hydric demands.

D) A specific example: the Reccopolis aqueduct

The aqueduct of Reccopolis (Fig. 5) was built ci. 578 to supply water to the newly founded city, established
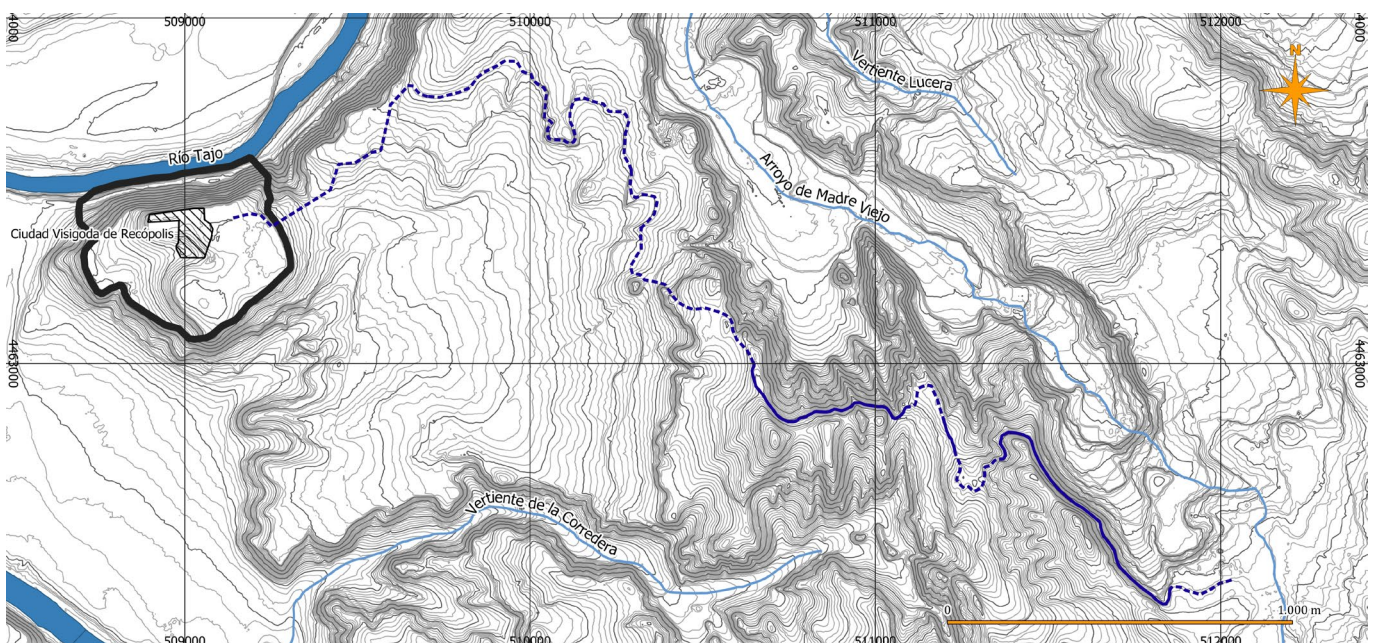

Figure 5. Map showing the course of the Reccopolis aqueduct, with known and projected sections, and the available water courses. Image by the author

by the Visigothic king Liuvigild to be a new regional centre in the province of Celtiberia (Martínez Jiménez 2015).[5] The construction is not Roman per se, but it is built following Roman and late Roman principles.[6] Currently, 2.3 km of its course have been identified through field surveys, and its total length has been calculated to have been around 5km. It was built as a mortared rubble semi-buried conduit, which ran at ground level through most of its course, following the contour lines, although at points there is evidence for high walls and, probably, arcades. Technically, it consists of a rectangular *substructio*, on average 1m high (including the foundation) and 1.4m wide, built in mortared rubble, and lime washed on its walls (Fig. 6). The conduit proper, the *specus*, has a cross-section 50cm wide and 40cm deep, lined with

Figure 6. Picture of the remains of the aqueduct. Image by the author.

a 2cm layer of *opus signinum*. The cover has been lost, although it is doubtful it was vaulted. Most probably the *specus* was covered with flat tiles or slabs.

The mortared elements for which water consumption can be calculated are the mortared rubble of the *substructio*, the *opus signinum* lining of the *specus*, and the external limewash, which was applied to the sides of the construction (Fig. 7). These calculations will ignore the use of mortar in the cover and those areas where the aqueduct might have run on higher walls or arches. As a result, the final calculations represent a significantly low estimate.

Figure 7. Detail of the limewash preserved on the walls of the aqueduct at the site of La Paeriza. Image by the author.

Opus signinum lining

The *opus signinum* of the Reccopolis aqueduct is a 2 cm thick mortar lining that probably ran for 5000m and covers three sides of a conduit that measures 0.5 by 0.4 m. This gives a total volume of 130m³ of *opus signinum*.

$$V_s = 5,000 \times (0.4 + 0.5 + 0.4) \times 0.02 = 130m^3$$

Since it is a lining, the value of β is 1. A macroscopical analysis of the lining shows that it uses a very coarse chamotte and that it contains a significant proportion of sand (potentially a 1:1:1 lime-chamotte-sand mix). For the γ variable, we will consider a value between 0.6 and 0.7, and a δ value of 2. For the rest, we need to keep to the ranges calculated above, without any further adjustments. With this, we can calculate S (slaking water) and R (rheologic water), but that leaves out C, the water added to the building blocks (*caementa*). However, since

the *opus signinum* would have to be applied to the inside walls of the conduit, these would also have to be wetted before plastering (to prevent the stone blocks to absorb moisture from the mortar). For this, we can assume that α is 1 and that the maximum value of ε is that of sandstone, 0.512.

These values give us a water input for the lining between 77 and 192m³, the equivalent of 59-147% of the volume of *opus signinum* (Tab. 6).

Table 6. Reccopolis aqueduct: final calculations for water consumption in the mixing of the *opus signinum* lining of the *specus.*

	Vol. (m³)	Vol. (%)
C (water used to soak *caementa*)	39.91	30.7
R (water to correct mortar rheology)	18.44-60.24	14.2-46.3
S (water consumed in slaking)	18.95-91.8	14.6-71.6
TOTAL	77.31-191.95	59.5-147.7

Mortared rubble substructio

The main structure of the conduit consisted of a solid mortared rubble core with two walls that encased the channel, geometrically simplified to a hollowed rectangle. The structure was, again, some 5,000m long, and on average 1m tall and 1.4m wide. If, to this volume, we deduct the volume occupied by the *specus* (same length, 0.4m tall and 0.5m wide) we obtain a solid with a volume of 6,000m³.

$$V_s = 5{,}000 \times 1 \times 1.4 - 5{,}000 \times 0.4 \times 0.5 = 6{,}000\text{m}^3$$

As mentioned earlier, for this particular structure the values of α and β are 0.7 and 0.3 respectively. The blocks used in the construction were made of limestone (max. ε = 0.307). The mortar was quite sandy, without any other noticeable aggregates, which suggests we can use 0.75-0.85 for γ and 3 for δ, comparable to other late antique hydraulic constructions (Snyder 2020). The generally calculated ranges will be used for the rest.

In this case, at 2000m³, the volume of water obtained is much larger than the one for the *opus signinum* (Tab. 7), which was to be expected since the structure is far more voluminous. However, the percentage of water relative to the volume of the structure is much lower

(28-46%), because most of the aqueduct's *substructio* is formed by building blocks, and only 30% of it is mortar.

Table 7. Reccopolis aqueduct: final calculations for water consumption in the mixing of the mortared rubble.

	Vol (m³)	Vol (%)
C (water used to soak *caementa*)	1289.4	21.5
R (water to correct mortar rheology)	223.4-695.1	3.72-11.6
S (water consumed in slaking)	172.2-794.4	2.87-13.24
TOTAL	1685-2779	28.1-46.3

Limewash

The walls of the aqueduct (like the city walls, and the walls of the palace) were limewashed to protect the fabric of the construction. For the overall surface of the aqueduct, we can expect two limewashed faces, approximately 1m in height. This results in a whitewashed surface of 10,000m². Considering the formula, the amount of water necessary to limewash the walls of the aqueduct ranges between 3.5 and 4m³.

Building the Reccopolis aqueduct: a thirsty project?

To build the aqueduct of Reccopolis, which, in terms of size, was more modest than an average aqueduct (Sánchez López and Martínez Jiménez 2016), between 1,765 and 2,975m³ of water were needed. It would be safe to assume that the bare minimum, considering all the variables that cannot be calculated or that have not been taken into account, would have been closer to 2,000. That is 60% of an Olympic-sized swimming pool to be sourced, transported, and stored throughout the duration of the project.

Reccopolis is conveniently situated between the Tagus (at the foot of the hill where the city is built) and the Madre Vieja, which was diverted to feed the aqueduct (Henning *et al*. 2019; Martínez Jiménez 2015). These two water courses are constant throughout the year and flow in abundance, making them the ideal candidates from which water for construction was obtained. The Tagus, as the main river, lies at the very bottom of the territory of Reccopolis; from the bottom of the valley to the point where the aqueduct taps the Madre Vieja there is

an altitude difference of 160m. The city itself is between 45 and 60m above the river level. Taking water down from the Madre Vieja along the course of the conduit would have been the most cost-efficient way since the water could be carried downhill along an existing road.

Water would have to be carried from either river to the various mixing stations we can expect to have existed along the course of the aqueduct. It may well be that there was a main lime burning and slaking facility next to the Tagus (the whole city was being built at the same time as the aqueduct). This would have reduced the water demands elsewhere along the aqueduct by several hundred cubic metres (and facilitated the maturing of the lime), but at least a thousand cubic metres of water were still needed to be taken to the mixing stations during the course of the construction. Regardless of how water was stored at these stations, we still have to imagine hundreds of trips with ceramic containers or skins full of water. A donkey can carry up to 50kg (Bukhari *et al.* 2021), so it would take more than 20 donkey loads to transport a cubic metre of water. For the Reccopolis aqueduct, this means 40,000 donkey trips.

As outlined in the introduction, these calculations are not aimed at giving a precise volume to the closest litre of water input; these are calculations to quantify the magnitude of water consumption in a given construction project. This should be a starting point to think about the necessary logistics associated with water sourcing, storing, and distribution, since water (as opposed to bricks, sand, rubble, or timber) cannot be piled in the corner of a yard.

IV. CONCLUSIONS

The exact amount of water that was required for any given construction project in Antiquity (what was termed *A* at the beginning of this paper) will never be known. The different processes involved in mortar mixing, lime slaking, and concrete construction are too complex and include too many circumstantial variables which cannot be gauged with accuracy. But accurately calculating that was never the aim of this paper; the objective of this article is to provide a guide to roughly estimate water input at four of the various stages in the *chaîne opératoire*: the water used for slaking (*S*), the water used to mix the mortar (*R*), the water used to soak the building blocks (*C*) and the water needed to limewash a wall (*P*). Similarly, this article focuses on Roman construction, using archaeological and literal examples from the period,

but the building principles are similar and comparable throughout the pre-Modern era.

The results of these calculations depend on the variables defined by the building materials and the mixing proportions. In the end, they offer us a range and an order of magnitude, which should be sufficient to think more carefully about the water logistics in large construction projects. Works that require only a few cubic metres of water might have required barrels for their storage, and these could have been filled from fountains, wells, or cisterns, but moving into the tens (or hundreds or thousands) of cubic meters required different solutions.

Further studies applicable to individual mortars will, naturally, nuance these calculations. Microscopic analyses revealing high proportions of unslaked nodules in the mortars may suggest the use of hot mortars ('volcano' mixes, where the hydration of the quicklime was not thorough) as opposed to the use of pre-slaked putties. The water needs on site of these two different techniques would vary, and so would the necessary logistics. In drier areas, like North Africa, meeting the hydric requirements of mortar construction might have been an impediment, but this opens new possibilities to explore ─ possibilities that might have been also necessary elsewhere in the ancient Mediterranean, like the role of aqueducts in the expansion of concrete and mortar constructions or the seasonal nature of construction processes.

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