Archaeological and Anthropological Sciences (2021) 13:192
https://doi.org/10.1007/s12520-021-01395-0

ORIGINAL PAPER

Mortars and plasters—How mortars were made. The literary sources

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Received: 18 January 2021 / Accepted: 30 June 2021

Abstract

This article examines the ancient literary evidence for information regarding the ingredients and processes employed to make mortar, plaster, and sealants. The information from the authors is examined chronologically and within the genre and literary context in which it occurs to evaluate better the intention of the author. The challenges presented by the transmission of the manuscripts to the modern day and by the ambiguous and technical language sometimes employed are presented. Terms and expressions are compared between authors to determine how and to what degree such ambiguities can be resolved. The goal is to present a methodology for approaching ancient texts rather than to provide a definitive interpretation of their meaning, a task which is sometimes not possible given the nature of the evidence. Finally, a series of best practices is suggested for those approaching the texts without the benefits of philological training.

Keywords Mortar · Plaster · Lime · Gypsum · Pozzolana · Clay · Daub

Premise

This Topical Collection (TC) covers several topics in the field of study, in which ancient architecture, art history, archaeology and material analyses intersect. The chosen perspective is that of a multidisciplinary scenario, capable of combining, integrating, and solving the research issues raised by the study of mortars, plasters, and pigments (Gliozzo et al. 2021).

The first group of contributions explains how mortars have been made and used through the ages (Arizzi and Cultrone 2021, Ergenç et al. 2021, this paper, Vitti 2021). An insight into their production, transport, and on-site organization is further provided by DeLaine (2021). Furthermore, several issues concerning the degradation and conservation of mortars and plasters are addressed from practical and technical standpoints (La Russa and Ruffolo 2021; Caroselli et al. 2021).

The second group of contributions is focused on pigments, starting from a philological essay on terminology (Becker 2021). Three archaeological reviews on prehistoric (Domingo Sanz and Chieli 2021), Roman (Salvadori and Sbrolli 2021), and Medieval (Murat 2021) wall paintings clarify the archaeological and historical/cultural framework. A series of archaeometric reviews illustrate the state of the art of the studies carried out on Fe-based red, yellow and brown ochres (Mastrotheodoros et al. 2021), Cu-based greens and blues (Švarcová et al. 2021), As-based yellows and reds (Gliozzo and Burgio 2021), Pb-based whites, reds, yellows and oranges (Gliozzo and Ionescu 2021), Hg-based red and white (Gliozzo 2021), and organic pigments (Aceto 2021). An overview of the use of inks, pigments and dyes in manuscripts, their scientific examination, and analysis protocol (Burgio 2021) as well as an overview of glass-based pigments (Cavallo and Riccardi 2021) are also presented. Furthermore, two papers on cosmetic (Pérez-Arantegui 2021) and bioactive (antibacterial) pigments (Knapp et al. 2021) provide insights into the variety and different uses of these materials.

Introduction

Ancient written sources present numerous challenges for those mining them for information on technical procedures in general and on mortars in particular. One must consider the goals and intended audience of a particular text

This article is part of the Topical Collection on *Mortars, plasters and pigments: Research questions and answers*

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Published online: 13 October 2021

whether it be literary or inscriptional. For literary works, the descriptions of materials and processes are typically only small parts of larger works and can sometimes be used for rhetorical purposes that subvert or obscure a more literal understanding of the topic. Moreover, the modes of transmission from antiquity to the present add a layer of difficulty. The copying of manuscripts by hand also introduced human error. Even more critical are the problems of interpretation that come when translating the original Latin or Greek into modern languages.

References to mortar and plaster occur in both Greek and Latin texts; however, not all of them provide insight into how mortars were made or even how the ancients thought about their materials. In what follows, I focus mainly on those passages that deal in some fashion with the materials for and the preparation of mortars and plasters.

The sources

Many of the passages discussed here are in Latin, and the few Greek sources cited were largely written during Roman period. For the Hellenistic Greek world, the fourth century BCE Greek philosopher/natural scientist Theophrastus is the most informative, and he was often the source for later authors. Inscriptions of building contracts from the Classical and Hellenistic Greek world sometimes refer to mortars, but a great majority of them deals with construction in stone and timber. The most common reference is to plaster wall coverings, but there is rarely a description of its preparation. Only in the second century BCE in Italy with the burgeoning structural use of mortar do we find more detailed instructions. Cato the Elder (ca. 160 BCE), in his agricultural treatise, gives advice on choosing stones, building the lime kiln, and mixing the mortar. Varro (late first century BCE) in his treatise *Rerum rusticarum* references numerous Greek agricultural writers, but none of these has come down to us. The one extensive surviving Latin building inscription, the *Lex parieti faciendo Puteolana* (105 BCE), is unusual in providing a recipe for making structural mortar. This increased attention to the detail of mortar preparation in the contract comes with the rise of *opus caementicium* (Roman concrete) as a means of building structural elements, so the quality of the mortar became critical for the stability of the structure.

Later writers in a variety of genres provide information on the materials for and the processing of mortar and plaster. In addition to Cato and Varro, the agricultural writers Columella (first century CE) and Palladius (fifth century CE) are useful sources on constructional materials and their applications. Nevertheless, our primary font of information is the architect Vitruvius, who wrote *De architectura* around 25 BCE. Of the ten books making up the treatise, he devotes Book 2 to building materials and techniques, where he deals specifically with mortar and its ingredients, but he also refers to mortars and plasters in Books 5, 7, and 8. Faventinus (third century CE), a later writer on villa architecture, draws extensively from Vitruvius. Both agricultural and architectural treatises belong to genres that one might expect to provide technical details on building materials, but information can also be gleaned from writers in other genres, such as the geographies of Strabo (early first century CE), the encyclopedia of Pliny the Elder (mid-first century CE), the letters of Seneca (mid-first century CE), the medical text of Dioscorides (first century CE), the history of Dio Cassius (early third century CE), a poem in the form of a riddle by Symphosius (ca. 500 CE), and the etymological investigation of Isidore of Seville (early seventh century CE).

The three most closely related works are those by Vitruvius, Faventinus, and Palladius. The treatises of the latter two have sometimes been considered as mere epitomes of Vitruvius, but the reality is more complex. Faventinus (1) cites Vitruvius specifically as one of his sources. Analysis of all three works reveals that Palladius was drawing from Faventinus but not from Vitruvius (Plommer 1973: 2–3). Therefore, each later author emended what his immediate predecessor wrote. This lineage is important to consider when comparing the changes in information that occur between the three authors.

The transmission of the manuscripts

Two of the greatest challenges in understanding the relevant passages relate to the transmission history of the manuscripts and the interpretation of the technical vocabulary and syntax of the Latin and Greek. For many ancient texts, the transmission of the original text has been corrupted by numerous copyists through time resulting in different versions of the text. When multiple versions exist, they can be compared, but in the end, one of them must be chosen, and that choice can take us one step further from the author's original. The most informative passages are in Latin, which is a terse language with a relatively small vocabulary in comparison to ancient Greek. It is also subject to abbreviated constructions that present ambiguities allowing for broad interpretations of meaning. This becomes especially evident when one finds multiple different translations of a single passage or phrase. Finally, expert philologists with the skills to translate the texts often have less experience with building processes, which can lead to obvious misrepresentations of the original intended meaning.

Vitruvius's *De architectura*

Vitruvius's treatise is the most important surviving source on ancient architecture. However, he has not been served well by the complex history of the transmission of his manuscript, which resulted in mistaken spellings and interpolations by scribes. Indeed, Leon Battista Alberti, writing in 1450, commented with frustration that Vitruvius "spoke so that to Latins he would have seemed a Greek, and the Greeks would have guessed him to be a Latin. The book itself will attest that it was neither Latin nor Greek; so he might as well never have written it at all, since he wrote in a way that we don't understand" (*De re aedificatoria* 6.1; trans. Rowland 2011: 287). To rectify the situation that had faced Alberti, the monk and celebrated architect Fra Giovanni Giocondo took it upon himself in 1511 to produce a more coherent version of the *De architectura* by combining his own excellent philological skills with his architectural background to re-examine various versions of the manuscript and to create a single more coherent edition (Giocondo 1511). Translations into modern European languages are based largely on Giocondo's edition. Thus, when reading Vitruvius in a modern language, one is hindered not only by the filters through which the Latin itself has passed over the centuries but also the filter of translation (Ciapponi 1984; Rowland 2011: 287).

Instructions for use

The following sections are divided into three parts: binders, fine aggregates, and methods of processing. For each discussion, the relevant ancient sources are presented chronologically earliest to latest as a way of examining how the information might have changed over time. In some cases, the later authors can help to clarify what an earlier author said. In others, they may add information that indicates an increase in the understanding of, or a change in attitude towards, a particular material or process. For problematic passages, I present the issues causing the difficulty in interpretation, but I do not necessarily attempt to solve the issue, which in many cases has no definitive answer due to the ambiguity of the evidence.

Binders

Mortar and plaster were substances used by ancient builders to construct walls of mortared rubble and brick (*opus caementicium*), to pave floors, to coat walls for decoration and for waterproofing, to create decorative moldings, and to act as a sealant. They consisted of a binder (clay, lime, or gypsum), an additive to help consolidate the mixture (straw, chaff, hair, sand, volcanic ash, crushed terracotta), and water. Earthen-based binders were common throughout the Mediterranean before the increased adoption of lime-based mortar during the Roman period, and they continued to be used alongside lime-based mortars in certain contexts. The two main stone-based binders used by the ancient builders were slaked lime and calcined gypsum. Although the ancient authors distinguished between the two, they understood them to be closely related, and sometimes they are mistakenly conflated in the texts. Other types of naturally occurring substances were sometimes used for both binders and wall coatings, such as pitch, bitumen, and wax (Vitr. *De arch*. 1.5.8; 7.4.6; Plin, HN 16.158, 35.182, 36.166),[1] but the focus of this investigation is on the preparation of man-made mortars and plasters, so those materials will not be discussed here.

Earthen-based binders

Earthen-based binders and wall coatings were used long before the lime plaster became the norm.[2] Clay-based binders were often mixed with straw, chaff, or hair to help hold the clay together and to reduce shrinkage and cracking during the drying process. An inscription for the repair of the Long Walls at Athens specifies a binding material of clay (πηλός, *pēilós*) mixed with chaff or finely chopped straw (ἀχυρόωσις, *achyróōsis*) (Hellman 1999: 33–7). Cato (*Agr*. 38) advises to build a lime kiln with rubble (*caementa*) held together simply with clay daub (*lutum*). Vitruvius (*De arch*. 2.3) has a chapter on unbaked brick, which he notes should be made of a type of white clayey earth or red earth ("*terra albida cretosa sive de rubrica*"), which was mixed with chaff/straw (*palea*), but he does not mention any type of earthen-based binder to connect them. He does, however, specify using clay (*argilla*) mixed with hair (*capillus*) as a binding agent between the fired bricks of the *pilae* in the *suspensurae* in bath buildings (*De arch.* 5.10.2; followed by Faventinus 16; Palladius 1.40) and as a joint filler between the tiles of a hanging tile ceiling in a bath (*De arch.* 5.10.3; followed by Faventinus 17). That the use of clay binders continued for centuries is verified by Palladius (1.34.4) writing in the fifth century, who notes that some people build garden walls using clay daub (*lutum*) to bind the stones. Wattle and daub walls are also mentioned by Latin authors (Vitr., *De arch*. 2.1.2–3; Plin., *HN* 35.169).

Varro (*Rust*. 1.14.4) describes a different type of earthen wall construction, found in Spain and in the area around Taranto in southern Italy, that he describes as made of earth and gravel ("*ex terra et lapillis*") inside formwork ("*in formis*"). Pliny (*HN* 35.169) also mentions this technique, locating it in Spain and Africa, calling it "*formaceos*" because the earth (*terra*) is packed (*infercio*) between two wooden forms, a method that he contrasts with walls that

[1] For the use of pitch in Greek construction, see references in Martin 1965: 20, 66, 422–3.

[2] Vitruvius (*De arch*. 2.1), in his explanation of the origins of architecture, equates earthen-based mortars with more primitive stages of development and barbarian building methods, but the Latin agricultural writers make clear that they were commonly used in farm buildings.

are "built" (*struo*). This is what today is called *pisé de terre*. In excavations where an earthen wall has disintegrated *pisé* and mud brick can easily be confused, but as Varro notes *pisé* consists of earth and gravel, whereas mud bricks have a much higher concentration of clay (Russell and Fentress 2016: 133). Palladius (1.34.4) describes a wall made up of "*luto inter formos*," which probably refers to *pisé* as well. The technique continued to be used in late antiquity and is cited in the seventh century by Isidore of Seville (15.9.5).

Earthen-based substances were also used as plasters for coating walls. For the walls of a granary, we get three slightly different recipes. Cato (*Agr*. 92) instructs to make a daub (*lutum*) containing chaff/straw (*palea*) and oil lees (*amurca*) to coat the walls. Varro (*Rust*. 1.57.1–2) recommends a similar mix of clay (*argilla*), grain chaff (*acus*), and oil lees (*amurca*). Palladius's (1.19.2) advice for a granary is to plaster the walls with clay daub (*lutum*) mixed with *amurca* and dried olive leaves. In all three, the recipes involve substances typically found in a farm context: chaff/straw and leaves. A similar substance but without the *amurca* was used for grafting trees (Columella, *De Arborius* 8.2, 26.5), so this mixture of clay with organic materials seems to have been a multipurpose farm material. In an entirely different context, Vitruvius specifies a coating of clay (*argilla*) and hair (*capillus*) over the skins of the protective shelter (*testudo*) of a battering ram to defend it from fire (*De arch.* 10.15.1).

Vitruvius (*De arch*. 7.3.11) provides a special hybrid method of coating walls of *opus craticum* (i.e., framework of timber with mortared rubble infill) consisting of both daub and lime plaster. He laments that this type of mixed construction is prone to cracking when the timber swells after absorbing moisture of the plaster. Therefore, he recommends coating the walls with a first layer of daub (*lutum*) then nailing horizontal reeds to it, covering it with a second layer of daub and nailing vertical reeds, and finally covering it all with a layer of lime plaster made with sand and marble dust. This method creates a kind of hardened outer shell that allows some expansion and contraction of the inner wall.

Lime-based binders

Lime-based binders are the most common type mentioned in the literature. Lime is a substance created by the burning of calcium-based rocks such as limestone, travertine, or marble, at a high temperature (900° C) to create quicklime (CaO). Before it can be used for mortar, the quicklime must be slaked with water to create calcium hydroxide ($Ca(OH)_2$) (Eckel 1907: 96, 118–22; Adam 1994: 65–73; Giuliani 2006: 209–14). The quality of the lime used for mortar was determined by the type of stone and the duration and temperature of the firing. The firing time is affected by the form of the kiln, the heat of the fire, the type and size of stones, and their placement in the kiln. Temperature and duration of firing are different for each type of stone, so if a particular type of stone is fired for too short a time or at too low a temperature, the resulting quicklime is not fully calcined. A fine balance must be maintained for the highest quality material (Boynton 1980: 164–5).

Selecting the stones

Cato the Elder gives specific instructions on selecting stones for the best quality lime. He advises to "charge the kiln only with good stone (*lapidem bonum*), as white and uniform as possible (*quam candidissimum, quam minime varium*)" (Cato, *Agr*. 38.2, trans. Ash 1934). This last comment suggests that he clearly understood the benefit of firing like stones together. Vitruvius (*De arch.* 2.5.1), writing over a century after Cato, gives similar advice saying that lime should be made from white stone (*albo saxo*) or *silex*. This latter term, *silex*, refers simply to hard stones, unlike in modern parlance where it often refers to flint or a volcanic stone high in silica (e.g., the Italian *selce*).[3] Vitruvius adds to Cato's advice by noting that lime from dense hard stone (*"ex spisso et duriore"*) is best for structural uses whereas lime from porous (*fistuloso*) stone is better for plasterwork. Pliny (*HN* 36.174) uses both Cato and Vitruvius as sources. He recalled that Cato disapproved of lime made from different types of stones. He repeats that white stone is best and adds Vitruvius's advice regarding the best types of stone for structural mortar and plaster. However, Pliny goes against Vitruvius's recommendation of *silex* noting that "Lime manufactured from *silex* is condemned for both purposes" (trans. Eichholz 1962). Why he specifically condemns *silex* is unclear. He also adds his own advice, "It [lime] is more serviceable if it is produced from quarried stone than from stones collected on the banks of rivers." (trans. Eichholz 1962). Presumably this is because stones taken directly from the quarry will be of the same type whereas those gathered from a riverbank will be more varied. Finally, he notes that high-quality lime is made from the stone used for millstones (*molares*). The most common Roman millstones known today are those from volcanic areas made from highly siliceous stones that are not composed of calcium carbonate and would not have produced lime (e.g., from Bolsena (*HN* 36.136), Orvieto, Mt. Vesuvius, Sardinia, Pantelleria) (Buffone et al. 1999; Lancaster et al. 2010; Peacock 1980). However, hard limestone was also used for millstones in non-volcanic zones. Pliny probably refers to millstones as a way of emphasizing the hardness of the stone.

Faventinus (9), writing in the third century CE, builds on his predecessors by adding examples of stone to be used for

[3] For example, Pliny (*HN* 36.135) refers to *silex* from Luna, which should indicate Luna marble.

lime: "Lime should be burned from white stone (*albo saxo*), or travertine (*tibertino*), or gray river stone (*columbino fluviatili*), or from red stone (*rubro*) or sponge-stone (*spongia*)" (trans. Plommer 1973). *Spongia* here must refer to calcareous tufa rather than volcanic pumice or scoria.[4] The addition of travertine to the list implies that *spolia* were being burned for lime by this period. By the third century, the travertine quarries at Tivoli were not as active as they once were, so he is unlikely to be referring to freshly quarried travertine. The increased use of *spolia* is also implied when Palladius (1.10.3) repeats Faventinus's list but adds marble (*marmor*) at the end of it. The practice of burning marble in earlier times when Vitruvius or Pliny was writing would have been unthinkable. However, it had certainly begun by the fourth century when a proclamation of 349 CE prohibited taking columns, marble, or stone from tombs for the purpose of burning them for lime (*Cod. Theod*. 9.17.2).

Firing the stones

Once the stones were gathered, they were fired in a lime kiln. The only ancient source for the construction of a lime kiln is Cato the Elder. Before describing how to build the kiln, he explains the typical terms of a contract between the person firing the stones (*calcarius*) and the owner of the property (*dominus*), "The burner prepares the kiln, burns the lime, takes it from the kiln, and cuts the wood for the kiln. The owner furnishes the necessary stone and wood for the kiln." (Cato, *Agr.* 16, trans. Ash 1934). As for the kiln itself, he says that it should be about 20 feet tall with as much of it as possible dug below ground level to minimize exposure to the wind. It should be 10 feet in diameter at the base tapering to 3 feet across at the top. He notes that when the flame coming out of the top of the kiln becomes less smokey, that is a sign that the uppermost stones are calcined and that the process is coming to an end (Cato, *Agr.* 38). He does not specify how long the firing should continue, but Alberti (*De re aedificatoria* 2.11) says that stones for lime must be fired for at least 60 h (about two and half days.)

The firing of the stones removes the moisture, and the stones become much lighter. According to Vitruvius (*De arch*. 2.5.3), they will have lost one-third of their weight when they are removed from the kiln. Alberti (*De re aedificatoria* 2.11) also repeats this observation adding that this is the criterion for the quicklime to meet the requirements of experts in his day. Vitruvius's statement, however, is made in the context of explaining the character of the physical makeup of the stone rather than as a prescription for judging quality. So, one should not assume that Vitruvius's comment was a type of quality test in antiquity.

The lightweight stones that come out of the lime kiln consist of calcium oxide (CaO), known as quicklime. In Greek, it was called ἄσβεστος τίτανος (*ásbestos títanos*), meaning "unquenched lime" (Galen, *MM* 5.325 k, 14.967 k; Plut., *Vit. Sert.* 17) or sometimes simply ἄσβεστος (*ásbestos*) (Dioscorides 5.115), or τίτανος (*títanos*) (Arist., *Mete*. 4.11.389a).[5] Lime was also sometimes called κονιά (*koniá*).[6] Plutarch (*Vit. Sert.* 17) compares the consistency of ἄσβεστος (*ásbestos*) to ashes (τέφρα, *téfra*) and elsewhere (*Vit. Eum*. 16.6) to dust (κόνιν, *kónin*). In Latin, quicklime was *calx viva* (Vitr., *De arch*. 8.6.8; Faventinus 6, 19; Augustine, *City of God* 21) and was typically considered to be either in powder form (Vitr., *De arch*. 8.6.8; Faventinus 6, 19) or fresh from the kiln in lumps (*glaebae*).

Quicklime is highly caustic and volatile. If exposed to humidity, it is subject to "air slaking"—when the moisture in the air causes the calcium oxide to recombine with carbon dioxide slowly to produce calcium carbonate. If this occurs, the quicklime loses potency and becomes inert. Thus, care had to be taken to protect it from air and moisture. This characteristic was recognized in Renaissance times as shown by Alberti's comment that the quicklime should not be allowed to lie around for too long after firing, "For if it is left in the kiln, or anywhere else where it might be exposed to breezes, the moon, or the sun, especially in summer, it will very soon turn to ashes and become useless" (*De re aedificatoria* 2.11, trans. Rykwert et al. 1988: 55). Today, air-slaked lime is also called "wind-slaked," a phenomenon that would account for Alberti's reference to breezes. No direct references exist in the ancient literature to air slaking, but a comment by Pliny (*HN* 36.177), noting that lime for stucco should always be slaked when it is in lumps (*glaebae*), may have been intended to avoid using air-slaked quicklime that had begun to deteriorate.

Slaking the lime

In order to make mortar, quicklime must be combined with water to produce calcium hydroxide ($Ca(OH)_2$), or slaked lime. During this process the lime-water mixture becomes very hot and emits steam as the calcium oxide combines with the water. This exothermic reaction held great fascination for

[4] Vitruvius (*De arch*. 2.6.2–3) uses "*spongia*" to refer to a type of volcanic scoria.

[5] Procopius (*Aed*. 1.1.53) (sixth century CE), when describing mortar, equates ἄσβεστος (*ásbestos*) with τίτανος (*títanos*), when he actually seems to be referring to mortar rather than lime. Elsewhere (*Aed*. 2.1.10, 3.3.12) he refers simply to τίτανος (*títanos*) again in a context that seems to refer to mortar. His use of both terms to signify mortar rather than lime could reflect a change in usage over time.

[6] Theophrastus, *On Stones* 9, 68; For discussion of Greek terms for lime, see Orlandos 1966–68, vol 1: 136–8.

ancient writers. Vitruvius (*De arch*. 2.5.2) comments on the heat generated by the slaking process. He explains that if limestone is simply pulverized to a powder without firing it and then mixed with water, it will not solidify or bond with anything. Then, he contrasts the powdered limestone with the behavior of quicklime rationalizing that the latent heat left in the calcined stones from the firing comes out in the slaking process. Pliny (*HN* 36.174) found the exothermic reaction of slaking lime in water to be miraculous (*"mirum*"), and he used slaked lime as an example of a counterintuitive natural phenomenon noting that it was ignited by water but extinguished by oil (*HN* 33.94, repeated by Augustine, *City of God* 21).[7] For the late antique author, Symphosius, the slaking of lime even became the crux of a poetic riddle entitled "*Calx*":

> "I have escaped the flames, I have fled the torments of fire. The very remedy opposed to my fate fights with it: I am kindled by liquids; I take fire from water though in its midst." (*Aenigmata* 75, trans. Ohl 1928).

Various terms in Latin were used to refer to slaked lime: *calx macerata* (soaked), *restincta* (quenched), *extincta* (quenched), *temperata* (tempered), and *intrita*.[8] *Intrita* seems to imply that the lime has been worked into a paste for use with plaster, whereas *macerata*, *restincta*, *extincta*, and *temperata* simply refer to the lime that has been slaked.[9] The most closely related term in Greek is κονιάμα (*koniáma*) (a variation of κονιά (*koniá*), which generally refers to lime); however, κονιάμα (*koniáma*) does not refer specifically to slaked lime but rather to plaster, in which the slaked lime has been mixed with fine aggregates.[10]

Ancient authors agree that for preparing plaster, the quicklime should be slaked for a long time to achieve the best quality. The longer it was left to soak the more of it dissolved and was converted to calcium hydroxide. Vitruvius (*De arch*. 7.2.1) recommends slaking the lumps (*glaebae*) of quicklime for making plaster long before using them so that any imperfectly burned pieces have plenty of time to soften, because the unslaked pieces can cause damage to plaster walls. As a test for proper slaking for plaster (*opus albarium*), Vitruvius (*De arch*. 7.2.2) advises to use an *ascia* (literally an axe or but most likely a type of hoe) to chop up the lime in its pit (*"in lacu*"), and if no lumps are encountered and the lime sticks to the blade like glue, it is ready to be used.[11] Pliny (*HN* 36.176) too indicates that older slaked lime is best for plaster citing an ancient law that contractors should not use lime slaked less than 3 years earlier. His reference to an ancient law implies that this was not always the practice in his own day. Vitruvius's (*De arch*. 7.2.2) slake test for lime is repeated by Pliny (*HN* 36.177), Faventinus (20), and Palladius (1.14–15).

Gypsum-based binder

In modern English parlance, "gypsum" refers to the mineral and the suite of stones composed of it, such as alabaster and selenite, whereas calcined gypsum is called "plaster of Paris." The ancient authors, however, did not make the distinction between the fired and unfired substance; thus, *γύψος* (*gýpsos*) in Greek and *gypsum* in Latin can refer either to the stone or the calcined powder. Gypsum-based plaster is made of a mineral consisting of calcium sulfate dihydrate, ($CaSO_4 \cdot 2H_2O$). By heating the stone to around 120°–180° C (Bailey 1932: 276), the carbon dioxide is driven off producing calcium sulfate hemihydrate ($CaSO_4 \cdot 0.5H_2O$), or plaster of Paris. If the temperature becomes too high, the resultant material will not recombine with water and cannot be used for mortar, so careful control is necessary. Using gypsum-based plaster has some advantages over lime-based plaster in that it is much cheaper to process due to the lower calcining temperature, and its burn time is much shorter. Alberti (*De re aedificatoria* 2.11) notes that gypsum requires only 20 h in the kiln as opposed to 60 h for quicklime. Unlike quicklime, calcined gypsum does not require slaking. It also has a very quick set time, which can be controlled to some degree—the longer the mixing, the quicker the set. This is beneficial when a fast-setting adhesive is required. However, gypsum plaster is also more soluble in water than lime plaster and can deteriorate in moist conditions.[12] Moreover, it does not have the same chemical potential as slaked lime to combine with high silica additives to produce a hydraulic mortar.

[7] Pliny (HN 33.94) also mentions a type of stone with similar properties from Thrace (*Thracius lapis*). This comment is probably taken from Theophrastus (*On Stones* 13). See commentary in Caley and Richards 1956: 80–3.

[8] *Macerata*: Vitr., *De arch*. 7.2.1, 7.2.2; Plin., *HN* 36.177; Faventinus 20; Palladius 1.14. *Restincta*: *Lex parieti faciendo Puteolana* 2.16–21. *Extincta*: Vitr., *De arch*. 2.5.1; Faventinus 20; Augustine, *City of God* 21. *Temperata*: Palladius 1.9.4.

[9] *Intrita* is only used by Pliny (*HN* 36.176). The meaning can be inferred from the context and from his other uses of the adjective.

[10] For κονιάμα (*koniáma*) as plaster: Demosthenes, *Orations* 13. *On Organization* 30; Aristotle, *Problems* 11.7; Diodorus Siculus 5.12.2, 20.8.3; Philo of Alexandria, *De agricultura* 37.160, *De Cherubim* 29.104.

[11] Quicklime can be slaked so that it becomes a putty or a powder. To create a putty, more water than lime is used, whereas if less water is used, the quicklime is hydrated to a powder with the excess water being removed as steam, as is common nowadays. Hydrated lime powder can then be combined with water later to create a lime putty for mortar. The implication of the ancient writers is that slaked lime was used in putty form.

[12] Wiss et al. 1930; Eckel 1907: 14–15, 31–2. Strength: Merriman 1920: 433.

Theophrastus, in his short treatise, *On Stones*, is most informative on gypsum, but his discussion is sometimes confusing because he seems to use the Greek *γύψος* (*gýpsos*) to refer to both gypsum-based and calcium carbonate-based stones, as well as other unconsolidated mineral deposits that would not have been used to make plaster (Bailey 1932: 276; Healy 1999: 211–12). Theophrastus (*On Stones* 64) introduces *gýpsos* as a naturally occurring substance used for treating clothes and notes that it is found near Mt. Athos and Cyprus. He contrasts this with its manmade version produced by burning stones, which he says was common in Phoenicia and Syria, and at Thurii in southern Italy. The fired stones refer to gypsum for making plaster of Paris whereas the substance for treating clothes is some other type of unconsolidated mineral deposit. In another passage, he says "After it has been pulverized and water has been poured on it, it is stirred with wooden sticks; for this cannot be done by hand because of the heat." (*On Stones* 66, trans. Caley and Richards 1956: 60). The reference in the first part of the phrase to pulverizing the fired stone before combining it with water accords with common practice for creating plaster of Paris, as described by Cato (*Agr.* 39) and much later by Alberti (*De re aedificatoria* 2.11), who specifies that fired chunks of gypsum must be beaten into a powder with wooden mallets before being added to water. However, the second part of the phrase referring to the requirement of using stirring sticks due to the heat generated is more descriptive of lime slaking. Plaster of Paris does generate an exothermic reaction, but it comes largely after it has begun to set rather than during the mixing. For example, today plaster of Paris is regularly mixed by hand with no adverse effects (personal experience). Quicklime, however, becomes extremely hot immediately upon contact with water and is also highly caustic to the skin (Caley and Richards 1956: 215). Theophrastus then goes on to say that "it is wetted immediately before it is used; for if this is done a short time before, it quickly hardens and it is impossible to divide it." Here, he is back to describing the behavior of plaster of Paris.[13] In a later passage, Theophrastus (*On Stones* 69) again uses *gýpsos* to refer to both lime and gypsum. He repeats that in Phoenicia and Syria, they fire *gýpsos* in a furnace, but then he adds that marbles (μαρμάρονς, *marmárons*) are burnt. The reference to marble, which is commonly burnt to create lime, suggests that he is not always distinguishing between stones that produce quicklime and those that produce plaster of Paris.

One finds the same type of ambiguity in Pliny (*HN* 36.182), who is relying directly on Theophrastus. Pliny points out that *calx* and *gypsum* are similar and notes that *gypsum* comes in several varieties. He repeats Theophrastus's comments that it is produced from calcining stone in Syria and at Thurii (leaving out Phoenicia). In describing what kinds of stone are fired, Pliny modifies Theophrastus's comment regarding marble, and says that the stone should be not dissimilar to *alabastrites*, or it should be marble-like (*marmoroso*). In fact, Pliny's *alabastrites* was stalagmite, a form of calcium carbonate, quarries of which are found near Thebes (Bailey 1932: pp. 276–7). Calcining it would have produced quicklime, not plaster of Paris.

Pliny (*HN* 36.182) also adds his own new information regarding the stones to burn for plaster of Paris noting that the best stone is *lapis specularis*. Elsewhere, Pliny (*HN* 36.160) refers to *lapis specularis* as a material that comes in thin translucent sheets, which could indicate either selenite or mica. In passage *HN* 36.182, he is clearly referring to the selenite because he locates the source for it in Spain around the city of Segobrigam, where ancient quarries of selenite have been found (Bernárdez Gómez and Guisado di Monti 2007). Both selenite and mica were used by the Romans for making windows (Guarnieri et al. 2015; Bailey 1932: 267), but only selenite could be burned to make plaster of Paris. Although Pliny does not distinguish between selenite and mica, the builders who prepared the plaster would have been able to acquire the appropriate material, even if this was simply by knowing the source of the stone.

Gypsum plaster is rarely mentioned by Latin writers. Vitruvius (*De arch.* 7.3.3) only mentions *gypsum* once—when he advises not to use it in the plaster for crown moldings (*coronae*) because it dries too unevenly. However, he is countered by Pliny (*HN* 36.183) who recommends it for making pleasing moldings (*"coronis gratissimus*") (followed by Isidore of Seville 16.3.9). Ancient authors do not mention the practice of adding gypsum to lime mortars, but analysis of the mortar at Trajan's Markets revealed traces of gypsum, which may have been added to speed the setting of the mortar (Ungaro et al. 1993: p. 191).

Fine aggregates

Fine aggregates are added to slaked lime putty to prevent excessive shrinking during the drying process as the moisture evaporates. When the proportion of fine aggregate is greater than that of the lime (see DeLaine this volume), the shrinkage of the mass is much reduced. If the fine aggregates consist of inert materials that do not react with the lime, such as river or sea sand, the resultant simple lime mortar hardens on contact with air. If they consist of reactive materials containing soluble silica, such as volcanic ash, crushed terracotta, or some types of organic ash, the resultant mortar is hydraulic, and it hardens by means of a chemical reaction that requires water to enable it to take place; hence, it grows stronger in the presence of water rather than air.

[13] For discussion, see Caley and Richards 1956: 214–15, 220–1.

The ancient authors did not understand the chemistry behind different types of mortar, but they were aware of the difference in quality and performance that came from using different types of fine aggregate. They divide fine aggregates into four main groups: river or sea sand (*harena fluviatica/marina*), quarry sand (*harena fossicia*), volcanic ash from the Bay of Naples (*pulvis puteolanus*), and crushed terracotta (*testae tunsae*). Today we understand that both *harena fossicia* and *pulvis puteolanus* refer to volcanic ash, but in the following sections, I treat them separately to reflect the ancient categorization.

Inert sand

The most basic type of fine aggregate was inert sand that did not react with lime but simply acted to strengthen the mortar and to reduce shrinkage. The two types mentioned by ancient authors are river sand (*harena fluvialis*) and sea sand (*harena marina*). Both types would have included quartz-based sands that contained insoluble silica, unlike the soluble silica in volcanic ash or fired terracotta. Cato, writing before the common use of volcanic ash (*harena fossicia*) in mortars, does not make the same type of distinctions as do later authors and simply specifies *"harena"* (*Agr.* 15). The resulting mortar he calls "*calx harenata*" (sanded lime) (*Agr.* 18). By the late first century BCE, Vitruvius distinguished between river sand (*fluvialis*), sea sand (*marina*), quarry sand (*fossicia*), and the powder (*pulvis*) from the Bay of Naples. In Book 2, he advises to use river or sea sand for structural mortar only if *harena fossicia* is not available (Vitr., *De arch*. 2.4.2). In the same passage, he explains that river and sea sand are less desirable than quarry sand because they create a weaker mortar that does not support vaulting (*concamerationes*) and that dries very slowly causing delay in the progress of the work. He adds that sea sand causes problems when used in plaster because it exudes a salty efflorescence that causes plaster to crumble. In Book 1, he had previously advised to use washed sea sand (*marina lota*) (Vitr., *De arch.* 1.2.8). Pliny (*HN* 36.175) lists three types of sand (*fossicia*, *fluvialis*, *marina*) but makes no further comments on their qualities. Faventinus (8) attributes the faults listed by Vitruvius for mortar made of river and sea sand to sea sand alone (slow drying, delaying the work, not supporting vaulting, salty efflorescence in plaster). Palladius (1.10.3) paraphrases Faventinus's passage, but he also adds specific instructions for how to wash sea sand by dropping it into a freshwater pool if it must be used for plaster. This detailed advice was perhaps intended to be of more relevance to his own audience, especially if they were building their villas along the coast.

Volcanic ash

By the second century BCE, Roman archaeological evidence shows that builders had discovered that adding volcanic ash, *harena fossicia* or *pulvis puteolanus*, created a stronger mortar and one that could harden under water. Vitruvius (*De arch*. 2.6.6.) considered them to be different substances and recommended them for different applications: *harena fossicia* for mortar in structures on land and *pulvis puteolanus* for marine structures. Today, we know that both consist of volcanic ash, but they are from different volcanic systems and have different physical properties, which make them appear to be different materials.

Harena fossicia

Vitruvius is the first to note the special properties of *harena fossicia* (quarry or pit sand) and to distinguish it from river and sea sand. He names four types: black (*nigra*), white (*cana*), red (*rubra*), and *carbunculus* (Vitr., *De arch.* 2.4.1). Pliny (*HN* 36.175) simply lists *harena fossicia* along with river and sea sand without distinguishing between the types of quarry sands. Faventinus (8), following Vitruvius, makes distinctions between them but only reports three types: black (*nigra*), red (*rubra*), and *carbunculus*, leaving out the white. Curiously, Palladius (1.10) names a different three from Faventinus: black (*nigra*), red (*rufa*), and white (*cana*), leaving out the *carbunculus*. Moreover, he is the only one to give evaluations on quality—he says that red is best, white is next, and black is last. Here again he changes Faventinus's advice. The fact that Palladius left out *carbunculus*, which Vitruvius locates in Etruria (see below), makes one wonder if, writing in the fifth century CE, he may not have been as focused on Rome and central Italy as were his predecessors.[14]

Identifying Vitruvius's *carbunculus* has been challenging for modern scholars, with various suggestions being made (Lugli 1957: pp. 398–9; Blake 1947: p. 42; Jackson et al. 2007). Vitruvius locates it as coming from Etruria (*De arch*. 2.6.4, 2.6.6) noting the many hot springs found in the area. He explains that:

> "…in those places where mountains are not earthy (*terrosi*) but are made instead of ligneous/plant matter (?) (*genere materiae*) the force of the fire exiting through veins scorches it. The fire consumes what is soft and tender and leaves behind what is rough (*asperum*). So just as in Campania the burnt earth becomes ash (*cinis*), in Etruria the dried out ligneous/

[14] Bartoldus 2012: pp. 15–35 argues that Palladius was from Gaul based on a prosopographical analysis, but there is no internal evidence from the manuscript to prove it.

plant matter (*excocta materia*) becomes *carbunculus*. Although both are very effective in concrete work (*structuris*), one is better for structures on land, the other for structures in the sea. The consistency of the material is softer than tuff but more consolidated than earth because it has been scorched from within by the intensity of the vapor (*vaporis*) from deep below, producing in some places a type of sand (*harenae*) called *carbunculus*" (*De arch*. 2.6.6, trans. author, based on Oleson 2014 and Granger 1933).

Varro (*Rust*. 1.9.3) is the only other author who speaks of *carbunculus* in its geological context when he says:

"For there are many substances in the soil (*terra*) varying in consistency and strength, such as rock (*lapis*), marble (*marmor*), rubble (*rudus*), sand (*harena*), loam [coarse sand] (*sabulo*), clay (*argilla*), red ochre [red earth] (*rubrica*), dust (*pulvis*), chalk (*creta*), ash (*cinis*), *carbunculus* (that is, when the ground becomes so hot from the sun that it chars the roots of plants (*radices satorum*))" (trans. Ash 1934).

Here too, Varro associates it with charred plant matter. The volcanic systems north of Rome, the Sabatini, Cimini, and Vulsini, produced a variety of consolidated and unconsolidated volcanic ash. Sometimes, the chunks of ash found within consolidated tuff contain the charred remains of plant material (personal observation). Perhaps, *carbunculus* could refer to unconsolidated volcanic ash deposits in which the charred organic material caused both Varro and Vitruvius to believe it was the product of plants.

Vitruvius (*De arch*. 2.4.1) says that the first task in acquiring *harena fossicia* is to distinguish between sand (*harena*) and earth (*terra*). Volcanic deposits are typically separated by a layer of earth that built up during the millennia between explosive events, and the difference between them is not always visually obvious, so the ancient builders had to develop the skills of a geologist to identify *harena fossicia*. Vitruvius provides two tests for doing so:

"Of these [i.e., sand and earth], that which makes a crackling noise (*stridorem*) when rubbed in the palm is best; that which contains earth will not have the proper roughness (*asperitatem*). Similarly, if this sand is wrapped in a white garment and does not soil it or leave earthy matter behind when shaken out, it will be suitable" (*De arch*. 2.4.1, trans. Oleson 2014).

Since volcanic ash consists of vesicular glassy scoria, the pieces have the sharp edges of the broken bubbles, which would account for his description of the noise that it makes and of its texture as rough or sharp (*aspera*). Indeed, Vitruvius (*De arch*. 8.6.14) and Faventinus (4) refer to quarry sand as *harena aspera*. Faventinus (8) repeats Vitruvius's tests with only minor changes in wording. Palladius (1.10.1) then gives an abbreviated version of Faventinus, but he adds that a piece of linen could also be used for the test. Isidore of Seville (16.3.11) also gives the same tests in abbreviated form.

According to Vitruvius (*De arch*. 2.4.3), the quarry sand used for structural mortar should be freshly excavated because if left out and exposed to sun, moon, and frost it breaks down and loses efficacy so that walls built with it are no longer structurally sound. However, he also points out that freshly excavated *harena fossicia* is too fat/rich ("*pinguitudine"*) to be used in plaster. Faventinus (8) and Palladius (1.10) report the same information in abbreviated forms. All authors were distinguishing not only between the types of ingredients for fine aggregates but also the processing and treatment of them before mixing with lime.

The only author to indicate where *harenae fossiciae* were located is Vitruvius (*De arch*. 2.6.5). He says that they can be found throughout parts of Etruria and Italy but that they do not occur beyond the Apennines or further east in Greece or Asia Minor. Indeed, the west coast of Italy occurs along a subduction plate that created a string of volcanic systems from northern Tuscany south to Campania, Sardinia, and Sicily. However, Vitruvius was mistaken to say that quarry sands do not occur further east. Volcanic ash occurs on volcanic islands in the Aegean, such as Santorini, Cos, Melos, and Nisyros. Theophrastus (*On Stones* 21) mentions Melos and Nisyros as sources of volcanic pumice and sand, but he would not have necessarily been aware of the advantages of adding them to lime mortar (Lancaster 2015: 23 Fig. 29).[15] Archaeological finds indicate that by the second century CE, builders outside of Italy were using their own local quarry sands, as on Cos and in the Eiffel region along the Rhine in Germany, but no ancient author mentions these locations.[16]

Pulvis puteolanus

The volcanic ash found around the Bay of Naples captured the attention of ancient authors in ways that the *harena fossicia* never did. It was considered unique because it was known to make mortar become hard under water. The term often used today to refer to this ash is "pozzolana," which takes its name from the port town of Pozzuoli, the ancient Puteoli. Vitruvius first points to its special qualities, but he does not associate it specifically with Puteoli. He identifies a *pulvis* found around Baiae and in the area around Vesuvius (*De arch*. 2.6.1). In a later passage (*De arch*. 5.12.2),

[15] Orlandos (1966–68: 139–40) cites volcanic ash in some examples of Classical and Hellenistic mortars at Thera, Delos, and the port at Zea, so there may have been localized knowledge of the benefits of volcanic ash in lime mortars before the practice developed more fully in Italy.

[16] Cos: Livadiotti 2006: 183; Germany: Lamprecht 1984: 46–9; Massazza and Costa 1977.

he says that when building port structures under water, one should use the *pulvis* from the region stretching from Cumae (the northern tip of the bay) to the promontory of Minerva (the southern tip). A few decades later, Strabo (5.4.6), when speaking about the great harbor at Puteoli, describes moles extending into the sea as made of the local sand (ἄμμος, *ámmos*) mixed with lime, but he does not name the *ámmos* as being a product of that city. Seneca (*Q Nat.* 3.20.3), writing in the mid-first century CE, is the first to associate the ash specifically with Puteoli when he calls it "*puteolanus pulvis*" and asserts that it becomes rock when it touches water. Pliny (*HN* 35.166), writing slightly later, also associates the *pulvis* with the hills around Puteoli. Like Seneca, he claims that it becomes like stone on contact with water. Dio Cassius (48.51.3), writing in Greek, refers to it as (γῆ, *gē*) and locates it as coming from the hill behind Baiae, rather than from Puteoli. He also delves into the reasons behind its special properties, which suggests that he was relying on Vitruvius's description (*De arch*. 2.6.1) for his information.

Both Seneca and Pliny neglect to mention that the *pulvis* must be mixed with lime before it takes on such amazing characteristics. As with lime, the *pulvis puteolanus* was seen as having strange and unusual characteristics, and it was used for rhetorical purposes. Seneca (*Q Nat*. 3.20.3), in a discussion on rivers, was using the *pulvis puteolanus* to make a clever contrast regarding the danger of drinking from polluted rivers. He quotes a passage from Ovid (*Met.* 15.313–314) who states that the Cicones (a tribe in Thrace) have a river with water that will turn one's insides (*viscera*) to stone and will put a layer of marble on everything it touches. Seneca then explains this phenomenon as due to the sediments in the river and advises that the water should not be drunk.[17] He then contrasts these river sediments with the powder from Puteoli, which itself becomes hard on touching the water rather than causing other things to become hard. Obviously, the contrast would not work if he explained that the powder had to be mixed with slaked lime before this hardening could occur. For Seneca, the attribution of an unusual characteristic to *pulvis puteolanus* is part of a rhetorical device rather than an attempt to explain the actual material or how it can be used.

Pliny's comment about *pulvis* from Puteoli becoming hard on contact with water similarly is used for rhetorical effect. In Book 35 on the use of natural substances taken from the earth, he makes a contrast between materials used in ingenious ways by man as opposed to those endowed with special properties by nature. After introducing various creative uses of potsherds (a fabricated material), he ends with the example of adding crushed pottery to lime for creating strong and durable pavements (*HN* 35.165). In the next paragraph, he cites a material coming directly from nature with a similar property—the *pulvis* from Puteoli, which he says, becomes hard on contact with water (*HN* 35.166). Since his focus is on the contrast between man-made vs. nature-made, he does not mention that the *pulvis* must be mixed with (human-processed) slaked lime. He then goes on to cite other places where unique products of the Earth react with water to become hard, including earth from Cnidus (*HN* 35.167), which would belong to the same volcanic activity as the volcanic ash on Cos, just off its coast. In this case, the mention of slaked lime would have destroyed the overall theme of his discourse. He was no doubt aware that lime was required, given that he explained how mortar was made with *harena fossicia* and lime (*HN* 36.175), but in his discussions mentioning the *pulvis*, his goals are different from those where he discusses how to make mortar.

Archaeological investigation shows that *pulvis puteolanus* remained the prime choice for building marine structures; however, local types of *harena fossicia* were apparently also employed in marine structures as revealed in the analysis of mortar samples (Brandon et al. 2014: 153–9; Marra et al. 2016: 68). Nevertheless, the *pulvis* from the Bay of Naples had developed a reputation for having special characteristics, as demonstrated by the comments of Seneca and Pliny. Ironically, as the demand for volcanic ash for harbor works increased throughout Europe during the Early Modern period, the *harena fossicia* in Lazio, which was exported from the papal port of Civitavecchia, outsold the *pulvis puteolanus* excavated and exported from Pozzuoli, the port of the King of Naples (Gargiani 2013: 47, 338). The *pulvis* from around Pozzuoli is, in fact, more reactive than that from Lazio and is best for marine structures, but politics played a role in what materials were exported to whom during this period.

Crushed terracotta

Like volcanic ash, certain types of fired clay (terracotta) can contain large amounts of soluble silica, which when combined with slaked lime produces a reaction that results in a hydraulic mortar. Ancient builders had discovered as early as the Bronze Age that adding crushed terracotta to lime mortar increased its strength and durability.[18] Vitruvius (*De arch*. 2.5.1) clearly understood this when he recommended adding crushed and sifted terracotta to mortar made with river or sea sand to make it stronger. The fineness of the particles

[17] Seneca (*Q Nat.* 3.2.3) also notes that similar phenomena occur in some places in Italy, and he cites the waters of Albula, which is at Tivoli and is what created the travertine deposits there. So, this phenomenon is apparently the result of precipitation of calcium carbonate from the water.

[18] Chiotis et al. 2001: 330 found crushed terracotta in the paving plaster of the Mycenaean palace at Tiryns.

was an important aspect of its efficacy because the finer particles provide more surface area to react with the lime. Vitruvius is followed by Pliny (*HN* 36.175) who advises adding pounded terracotta (*testae tusae*) and Faventinus (9) who specifies *"testae cretae*,"[19] although neither of the later authors mentions sifting it. The use of crushed terracotta in structural mortar was generally not practiced in Rome where there was plenty of *harena fossicia*, but it was used in non-volcanic areas of the Empire to improve the strength of structural mortar (Lancaster 2015: 27, Fig. 29).

Crushed terracotta was often added to lime mortar for pavements and to lime plaster for waterproofing, as commonly recognized in the archaeological record throughout both the western and eastern Mediterranean. In Italian parlance, this mixture is called "*cocciopesto*" and in Turkish "*horasan*." Columella and Palladius seem to describe a paving of this type. Columella (*Rust.* 1.6.13) explains how to build the floor of a granary—he says to add a *pavimentum testaceum* above a beaten earth floor and then to add oil lees in place of water when mixing the lime and sand. The lime and sand clearly compose a mortar, but whether it makes up the *pavimentum testaceum* itself or is the setting bed for a tile floor is not clear. The passage has been interpreted both ways.[20] However, Columella then adds that the joint between the floor and the wall should be joined with a "terracotta cushion" (*"testaceis pulvinis"*). This phrase describes very well the rounded *cocciopesto* curbing that one typically finds at the base of the wall of cisterns and other liquid containment structures. Palladius (1.19.1) in his description of how to build a granary is clearer. He says explicitly that two-foot bricks (*bipedales*) form a layer separate from the *testaceum pavimentum*, which is cast (*soffuso*) into place. Elsewhere, Palladius (1.17.1) also describes the *testaceum pavimentum* floor of a cistern as being cast or poured ("*fusoriis*"). He then goes on to say that the same should be done for the walls. Palladius's descriptions of how the floor is put into place suggest that the *testaceum pavimentum* was indeed a mortar-based material containing crushed terracotta, like *cocciopesto*. Vitruvius and others also use *testaceum pavimentum* to describe the base layer under a floor of crushed charcoal mortar (Vitr., *De arch*. 7.4.5; Plin., *HN* 36.188; Faventinus 26; Palladius 1.9), which also must refer to a similar mortar-based subfloor, despite the numerous ambiguous translations that exist in various languages.[21]

The use of crushed terracotta mortar for ancient paving brings up a great debate regarding another term found in the ancient sources—*opus signinum*. The two most outspoken scholars on the issue have been C. F. Giuliani (1992, 2006; followed by Grandi Carletti 2001; Braconi 2009), who argues that the term refers to a dense compacted mortared rubble used to build cisterns, and P. Gros (2003, 2015), who argues that it refers to a paving of crushed terracotta mortar and is synonymous with *cocciopesto*. The ancient authors are not explicit on this matter. As seen in the example above, they do not always define their terms clearly. The literary evidence consists of the use of the term *opus signinum* by six authors (Vitruvius, Columella, Pliny the Elder, Frontinus, Faventinus, and Palladius). Of these six authors, only Pliny (*HN* 35.165) directly associates it with crushed terracotta mortar when he says:

> "What can experience not invent? Indeed, it has devised a way to use broken pots by adding lime to pulverized potsherds to create a type of hard and durable pavement, which they call [*opera*] *Signina*" (trans. author).[22]

"*Signina*" is an adjective referring to the town of Signia in Latium. Pliny (*HN* 15.55) again associates Signia with terracotta when speaking of the pear *(pira*) called "*signina*," which he says takes the name from its terracotta color. Thus, in Pliny's mind, there is a connection between the epithet "*signina*" and terracotta.

Ancient literary citations of *opus signinum* and crushed terracotta share features of similar contexts and processing method. The contexts in which *opus signinum* is cited include the following:

- a type of paving (Plin., *HN* 35.165)
- the paving of the edge of a freshwater duck/fishpond (Columella, *Rust.* 8.15.3)
- the lining of a coastal fish farm (Columella, *Rust.* 8.17.1)
- an element in the walkways in an open portico or exercise ground (*xystus*) (Vitr., *De arch*. 5.11.4)
- a cistern (Vitr., *De arch*. 8.14.6; Palladius 1.17.1)
- the intake outlet of an aqueduct (Frontin., *Aq.* 10.5)
- a well (Faventinus 4)

[19] The use of *"cretae"*, a word implying chalk, suggests that the *testae* were chalk-like or finely crushed.

[20] *Cocciopesto*: Giuliani 1992: 92; Tiles: Ash 1941: 71.

[21] Vitruvius (*De arch*. 7.4.5) refers to a "*testaceum pavimentum*," which has been translated as "a pavement …of pounded brick" (Granger 1935: 101), as "a terracotta pavement" (Rowland and Howe

Footnote 21 (continued)

1999: 91), and as "un pavimento di mattoni" (Corso and Romano 1997: 1043). In Pliny (*HN* 36.188), it is translated as "a layer of pounded potsherds" (Eichholz 1962: 149). In Faventinus (26) as "a pavement of earthenware" (Plommer 1973: 75) and "a pavement du tuileau" (Cam 2001: 33). In Palladius (1.9), as "a testaceous coat" (Owen 1807: 20) and as "un carrelage de briques" (Martin and Guiraud 1976: 17).

[22] I owe thanks to Eric Kondratieff and Bill Owens for their advice in helping me to interpret and translate this passage.

Table 1 Literary citations of *opus signinum* and crushed terracotta mortar. Light shading indicates examples with *opus signinum*. Dark shading represents examples where *opus signinum* is associated with crushed terracotta mortar. Authors are listed in chronological order

Citation	Context	*Opus Signinum*	Crushed Terracotta	Verb for "Compress"	Term for "Wooden Piles"
Cato, *Agr*. 18.7	paving		yes		
Vitr. *De arch*. 5.10.3	plaster on hanging ceiling		yes		
Vitr. *De arch*. 5.11.4	walkway paving	yes			
Vitr. *De arch*. 7.1.3	paving		yes	*solido*	*vectes lignei*
Vitr. *De arch*. 7.1.5–6	paving		yes	*pisto*	
Vitr. *De arch*. 7.4.1, 7.4.3	plaster on damp walls		yes		
Vitr. *De arch*. 8.14.6	cistern	yes	*testa* or *tecta*?	*calco*	*vectes lignei ferrati* (w/iron tip)
Columella, *Rust*. 8.15.3	paving of duckpond	yes		*inculco*	
Columella, *Rust*. 8.17.1	coastal fish farm	yes			
Plin. *HN* 35.165	paving	yes	yes		
Plin. *HN* 36.176	plaster on damp wall		yes		
Frontin. *Aq*. 10.5	aqueduct intake	yes			
Faventinus 4	well	yes		*denso*	*vectes lignei*
Faventinus 9	structural mortar		yes		
Faventinus 18	paving		yes	*calco, solido*	*vectes lignei*
Faventinus 19	paving		yes		
Palladius 1.17.1	cistern wall	yes			
Palladius 1.17.1	cistern paving, wall plaster		yes		
Palladius 1.19.1	granary sub pavement		yes	*imprimo*	
Palladius 1.40.4	vaults in a bath	yes			
Palladius 1.40.5	plaster on hanging ceiling				

- the vaulting in a bath (Palladius 1.40.4)

Alternatively, crushed terracotta mortar is cited in the following situations, but it is not called *opus signinum*:

- for structural mortar made with river sand (Vitr., *De arch.* 2.4.3; Faventinus 9)
- as the undercoat of plaster on a hanging tile ceiling in a bath (Vitr., *De arch*. 5.10.3; Palladius 1.40.5)
- as the undercoat of plaster on walls in damp conditions (Vitr., *De arch*. 7.4.1, 7.4.3; Pliny, *HN* 36.176)
- as paving (Cato, *Agr.* 18.7; Vitr., *De arch*. 7.1.3, 7.1.5–6, 7.4.4–5; Columella, *Rust.* 1.6.13; Pliny, *HN* 35.165; Faventinus 18–19; Palladius 1.17.1, 1.19.1)

Common advice for both *opus signinum* and crushed terracotta pavements is that the mixture should be compressed or tamped down. For examples in both categories, wooden piles (*vectes lignei*) are recommended for this task (Table 1).[23] In two places, *opus signinum* is mentioned as a comparison to illustrate a process (therefore, not listed as *signinum* in Table 1). Vitruvius (*De arch*. 2.4.3) cites it in the context of describing that plaster made with river sand should be polished to increase its solidity, as with *opus signinum*. Columella (*Rust*. 1.6.12–13) refers to it in describing how to prepare the earthen floor of a granary before laying the *pavimentum testaceum* saying that the earth "is packed down (*condensatur*) with rammers (*pilis*) as is Signian work (*signinum opus*)" (trans. Ash 1941). He goes on to say that the *pavimentum testaceum* should be treated in the same way.

The term *opus signinum* has long been associated with the modern equivalent of *cocciopesto*, and it appears frequently in archaeological reports. The association resulted from several factors: (1) the similarities of the contexts in which both *opus signinum* and crushed terracotta mortar were employed for paving, (2) the common advice to tamp them with wooden piles, and (3) Pliny's attribution of the term *opus signinum* to paving made of crushed terracotta and lime mortar. The argument of Giuliani and others who maintain that *opus signinum* is not related to *cocciopesto* focuses on a passage from Vitruvius (*De arch.* 8.6.14–15) in which he describes the construction of a cistern and specifies using *opus signinum*. The fact that this is the earliest surviving occurrence of the term has given this passage particular significance.

A closer look at Vitruvius 8.6.14 reveals the problems encountered in trying to understand the ancient texts. Gros

[23] The practice of compacting earth floors is mentioned much earlier by Cato (*Agr.* 129) where he recommends using a rammer (*pavicula*) or a roller (*cylindro*) for a grain threshing floor.

(2003; 2015: 228), arguing in favor of *signinum* containing crushed terracotta, approaches the problem from a palaeographic perspective. He argues that the problematic passage 8.6.14 in the *De architectura* is the result of a change made by Giocondo (1511) in his effort to make Vitruvius more coherent. In Giocondo's version of the Latin, the critical passage translates as follows: "Then, if the ground is hard or the veins [of water] are too deep, then supplies are to be collected from roofs or other high places by *opus signinum*." Giocondo's Latin for the underlined section of the translation reads "*signinis operibus ex tectis aut superioribus locis*". However, Gros points out that in pre-Giocondo manuscripts, the Latin phrase reads "*signinis operibus ex testis a superioribus locis*," which translates to "supplies are to be collected from high places by means of *opus signinum* made of potsherds"—thus, Giocondo replaced "*testis*" with "*tectis*" thereby changing the meaning from "potsherds" to "roofs."[24] After this introductory phrase, Vitruvius then uses the term again saying "*in signinis autem operibus haec sunt facienda*," which has been translated two different ways: "We must proceed thus in making the cement [*opus signinum*]" (trans. Granger 1935) and "In the case of a signinum mortar, here is what to do" (trans. French, Gros 2003: 482; English, author). The two different translations affect how one interprets what follows. The first implies that what follows is a description of how to make *opus signinum* whereas the second implies that what follows is a description of how to build the walls on which the *opus signinum* will be applied. The walls are described as composed of a mortar of lime and quarry sand that bind very hard, small stones, all rammed down into a trench with wooden rods sheathed in iron. Giuliani, reading from Giocondo's version of the Latin, argues that *opus signinum* should refer to the type of dense, mortared wall construction. He discounts Pliny's account as an "*errore banale*" (Giuliani 1992: 93; Giuliani 2006: 226). Gros, on the other hand, reads the pre-Giocondo Latin text as describing the wall construction that will be covered with a crushed terracotta mortar. Regardless of which version of the Latin text one accepts, the syntax of the Latin is difficult and the meaning ambiguous, which is why Giocondo thought it needed improving.

Looking to Faventinus for insight into Vitruvius's intention is of little help. Faventinus (4) gives a different version of *De arch*. 8.6.14–15 when he adapts the instructions to the construction of a well instead of a cistern. He mentions building walls of *opus signinum* at the beginning of the passage, but he does not provide much clarity on how this is done. For his part, Palladius (1.17) takes Faventinus's description of the well construction and applies it back to cistern construction. He first says that the walls of the cistern should be of *opus signinum* without describing further, and then he goes on to describe the *testaceum pavimentum*, discussed above, but there is no clear connection between the *opus signinum* of the walls and the *testaceum pavimentum* of the floor. Elsewhere, Palladius (1.40.4) also refers to vaulting of *signinum* when he says that "*signinum* vaults in baths are stronger" ("*camerae in balneus signinae fortiores sunt*"). Again, we encounter difficulties when tracing the lineage of the phrase. Vitruvius (*De arch.* 5.10.3), in his advice on building baths, says "the vaults will be more suitable if they are made of masonry" ("*concamarationes vero si ex structura factae fuerint*, *erunt utilitores*"). Faventinus (17) changes this to read simply "Masonry vaults will be stronger" (*"camerae structiles fortiores erunt*"). Then, Palladius inserts "*signinae*" in place of Faventinus's "*structiles*." This would imply that he thinks of *signinum* as a type of masonry. Unfortunately, the line of development from Vitruvius to Faventinus to Palladius does not help to clarify what each understood *opus signinum* to be, and indeed the meaning could have changed over time.

Proponents of the different interpretations place different emphases on some passages over others, have divergent interpretations of ambiguous language in the passages, and choose one version of the manuscript over another. Ultimately, we are left with a conundrum. Pliny clearly thinks that *opus signinum* refers to a crushed terracotta mortar pavement, but whether Vitruvius and others did is unclear given the problematic nature of the existing evidence including the difficult transmission history of the manuscripts. The safest approach for the modern scholar is to avoid using the term *opus signinum* to describe any ancient building method!

Charcoal and ash

Charcoal and ash are both found in ancient mortars and are sometimes erroneously considered to be two forms of the same material. In fact, they each have different properties when mixed with lime mortar. Certain types of organic ash (grass, grains, olive pits, herbivore manure) have high levels of silica, which when burnt can create ashes containing soluble silica that reacts with the lime to produce hydraulic mortar, whereas charcoal consists mainly of carbon, which does not react with lime (Lancaster 2019). The only mention of the practice of adding either type of burnt material to mortar comes in Vitruvius's (*De arch*. 7.4.5) advice to

[24] The early manuscripts have two variations of the phrase, but all read "*testis*." H (Harley 2767, ninth century) reads: *signis operibus ex testis aut*. Three others, E (Wolfenbüttel, Bibl. 132, tenth century), S (Selestad. Bibl 1153, tenth century), and G (Wolfenbüttel, Bibl. 69, eleventh century) read: *signinis operibus ex testis a* (Rose 1899: 208). For a listing of the various manuscripts of Vitruvius and their designations, see Granger 1933: xxxii–xiii.

adopt the Greek method for laying the pavement of winter *triclinia* (dining rooms). He advises to lay a flooring of rubble (*rudus*) or *testaceum pavimentum* ("*aut rudus aut testaceum pavimentum*") sloped towards a drain. We saw above that Columella and Palladius apparently used "*testaceum pavimentum*" to refer to a *cocciopesto* floor. Next, he says to collect charcoal (*carbo*), compact it by treading on it, and then spread a mortar mixed of coarse sand (*sabulo*), lime (calx), and ashes (*favillae*), and polish it. Finally, Vitruvius explains that when guests spill their wine or spit it out after tasting, it will be absorbed immediately. Pliny (*HN* 36.188) gives similar instructions for laying a Greek type of floor (*genus Graecani*) citing Vitruvius's language "*aut rudus aut testaceum pavimentum*" but without identifying room function. Faventinus (26) follows Vitruvius's advice, using the same phrase, and recommends it for a winter *triclinium* but does not name the method as Greek. Palladius (1.9) follows Faventinus, not noting the Greek origins, and omits the specification of a *triclinium* simply saying that it should be used for a winter habitation, but his comment that this type of floor absorbs liquid poured from a drinking cup suggests that he still has in mind a dining context. In this chronological sequence, the Greek origins important to Vitruvius and Pliny evidently no longer held cultural capital for the two later authors. One wonders if Palladius's omission of the term *triclinium* also could reflect changes in practices or nomenclature during the late antique period.

Vitruvius provides some hints behind the intended purpose of the charcoal in other passages. In advising to add a layer of charcoal under exterior pavements in particularly damp zones, he explains that the charcoal has a natural permeability that aids in draining water away from walkways (Vitr., *De arch*. 5.9.7). He also says to add charcoal between pilings when building in a swampy zone, presumably for the same reason—to allow for the water to drain away (*De arch*. 3.4.2). The layer of compacted charcoal under the *triclinium* pavement would have performed a similar function—any excess moisture that seeped down through the top layer could run off into the drain. The ashes (*favilla*) added to the paving mortar and the final polishing of it, in turn would have created a permeable but resistant surface, especially if the ashes were the result of burning organic materials with high levels of silica.[25]

Ash is often found used in addition to or as a substitute for crushed terracotta in the waterproof plasters of liquid containment structures, especially in Punic areas like North African, southern Spain, and Sardinia (Lancaster 2012). Ancient authors do not mention the use of organic ash in mortar beyond using the *favillae* in the *triclinium* floor, but the practice occurs frequently enough in some regions to assume it was an intentional choice, although in cases where there are minimal traces, the presence of ashes could be the result of contamination form the lime kiln (see DeLaine this volume).

Marble dust

Marble dust was often added to the final layers of wall plaster in both the Greek and Roman times.[26] Varro provides an early documentation of the practice in his *De Re Rustica* (ca. 37 BCE) when he advises to line the ceiling, walls, and floor of one's fruit storage room with marble plaster (*opus tectorius marmoratus*) to keep out vermin (*Rust.* 1.57.2). He recommends the same for lining a dovecote (*Rust.* 3.7.3). Vitruvius's advice to add marble dust is more focused on creating a smooth and lustrous surface (Vitr., *De arch*. 7.3.6–8). When plastering walls, he specifies that after the rough coats have been applied, then the final three coats are to be laid on with progressively finer layers made with marble dust (i.e., in place of sand). He says that marble dust imparts a pure whiteness to the plaster as well as providing strength and a sheen once polished, which in turn allows the painted images to have greater clarity (Vitr., *De arch*. 7.3.7–8; followed by Faventinus 1.22 and Palladius 1.15).

Processing methods

Some processing of the fine aggregates before adding them to the mortar mixture was clearly practiced if not always rigorously (see DeLaine this volume). Sifting both lime and fine aggregates is sometimes recommended. This was a practice long used in mining (Theophrastus, *On Metals*, frag. 198). Cato (*Agr.* 18.7) advises using sifted lime ("*calcem cribro subcretam*") for the topcoat on a floor. Vitruvius (*De arch*. 2.4.2) suggests sieving (*excerno*) river sand before using it in mortar (*De arch*. 2.4.2, followed by Faventinus 8), adding crushed and sifted terracotta ("*testam tunsam et succretam*") to mortar of lime and river/sea sand (*De arch*. 2.5.1), and sifting marble dust before using it in the final layers of plaster (*De arch*. 7.3.3, 7.6.1). Vitruvius (*De arch*. 7.6.1) also notes that one should select the right sort of marble for this purpose and to process it appropriately. He explains that some types can be found in chunks with shiny grains, which can be crushed and milled to be used in plaster, but when these are not available, one can acquire the pieces and chips from marble workers and crush (*contundo*), mill (*molo*), and sieve (*subcerno*) them. He ends by citing a marble powder around Ephesus and Magnesia that is so fine it does not need further processing, but what type of marble he had in mind is unclear.

[25] For the effects of polishing mortar, see Goodman 1989. For the hydraulic effects of organic ashes, see Lancaster 2019.

[26] For the use of marble dust in Greek wall plasters, see Martin 1965: 422–5; Orlandos 1966–68: 139.

Table 2 Ratios of lime to fine aggregates given for mortars and plasters given by ancient sources

Source	Use	Ratio Lime:Sand	Ratio Lime:Sand:TCotta	Ratio Lime:TCotta	Ratio Lime:*HarenFoss*	Ratio Lime:*PulvisPut*
Cato, *Agr*. 15	structural	1:2				
Lex Puteol. 2.16–21	structural					1:2
Vitr. *De arch.* 2.5.1	structural/plaster	1:2	1:2:1		1:3	
Vitr. *De arch.* 5.12.2	marine					1:2
Vitr. *De arch.* 7.1.3	paving			1:3		
Vitr. *De arch.* 8.14.6	cistern				2:5	
Plin. *HN* 36.173	cistern				2:5	
Plin. *HN* 36.175	structural	1:2	1:2:1	1:3		
Faventinus 4	well				2:5 (1:2 better)	
Faventinus 9	structural/plaster	1:2	1:2:1 (struct)			
Palladius 1.10	structural/plaster	1:2	1:2:1 (struct)			

Sand = river/sea sand; TCotta = terracotta; *HarenFoss* = *harena fossicia*; *PulvisPut* = *pulvis puteolanus*

Washing sea sand is recorded only by Vitruvius and Palladius. Vitruvius (*De arch*. 1.2.8) mentions using washed sea sand (*marina lota*) if it is the only type available, but he does not give a method of washing it. Faventinus does not mention washing sea sand at all, but then Palladius (1.10) explains that if it must be used for plaster, it should be washed in a freshwater pool. In the building of a cistern, Vitruvius (*De arch.* 8.6.14) advises using the purest (*purissima*) and sharpest (*asperrima*) *harena*. His use of *purissima* probably refers to *harena fossicia* that has been separated from any soil that may have contaminated it. He does not specify sifting the *harena fossicia* as he does for river sand (*De arch*. 2.4.2) or washing it as he does for sea sand, but he clearly has in mind processing it in some way or possibly taking it from a part of the quarry where it is less likely to be contaminated by soil.

Various authors also recommend polishing mortar surfaces both for strength and appearance. For the final layer of a mortar floor, Cato (*Agr*. 18.7) advises pounding it (*pavio*) and then rubbing it (*frico*). Likewise, Palladius (1.17) recommends rubbing (*perfrico*) the final floor surface. Vitruvius (*De arch*. 7.3.7) and Faventinus (22) note that polishing (*polio*) the final coat of wall plaster serves to strengthen it.

Methods and recipes for making mortar

The three main uses of mortars in building contexts were to bind structural elements, to coat floors, walls, and ceilings, and to create caulk for waterproof seals. In all cases, the ancient authors provide some guidance in how to mix the final substance.

Structural mortar

For mixing structural mortar, Cato (*Agr.* 15) gives a recipe of two *modii* of sand for each *modius* of lime. His use of the word "*modius*," a unit of volumetric measurement, indicates that the materials are measured by volume rather than by weight. He is the only author to specify a unit of measurement in giving the recipes for mortar, but the fact that later authors repeat his proportions suggests that they also are referring to ratios of volume rather than weight. As discussed earlier, the slaked lime would have been in putty form.

In addition to Cato's recipe, one other pre-Vitruvian recipe exists in the *Lex parieti faciendo Puteolana*, an inscription that gives the specifications for building a wall in front of the Temple of Serapis at Puteoli. It notes that the plaster for covering the walls should be made of lime and sand ("*calce harenato*"), but it gives no proportions. However, it follows with instructions for building the wall itself and specifies that the mortar is to be made of one part slaked lime (*calx restincta*) and three parts *"terra*". What is the meaning of *terra* in this context? Given that *harena* has already been cited as an ingredient in the plaster, *terra* is clearly something different. "Soil" makes no sense from a technical point of view. In Varro's (*Rust*. 1.9.3) discussion of the meaning of "*terra*," he notes that it includes many different types of substances including ash (*cinis*), dust (*pulvis*), and sand (*harena*), so *terra* is a term that could refer to a broad category of substances. In this case, it probably refers to the local *pulvis puteolanus* at a time before there was a name for it. In fact, *pulvis puteolanus* is much finer than river/sea sand or *harena fossicia*, which is why it is referred to later as *pulvis* rather than *harena*.

Vitruvius adds a few recipes to the ones given by Cato and the *Lex Puteolana*. In Book 2, he repeats Cato's lime to (river/sea) sand ratio of 1:2, but he advises that a better mixture is made by adding a third part of crushed terracotta (*testa tunsa*) (*De arch.* 2.5.1), which would give a ratio of lime:sand:terracotta of 1:2:1. Thus, the amount of lime is reduced when the crushed terracotta is added. He also reduces the proportion of lime to 1:3 when using *harena fossicia*, which is the same ratio given in the *Lex Puteolana* (2.16–20) for building on land with "*terra*" (*pulvis puteolanus?*). However, in Book 5, he gives a ratio of 1:2 when using *pulvis puteolanus* for building marine structures (*De arch.* 5.12.2). Vitruvius is the only source who gives a recipe for building in the sea with *pulvis puteolanus*. The fact that the *Lex Puteolana* gave a different recipe for using the *pulvis* for a building on land suggests that Vitruvius's decision to add more lime must, in his own mind, have been due to the marine context (Table 2).

Vitruvius (*De arch*. 8.6.14) gives another ratio for mortar when describing how to build the walls of an underground cistern. He gives the ratio of lime to sand (*harena fossicia*) of 2:5, which results in a percentage of lime (29%) somewhere between the 1:3 (25%) and 1:2 (33%) ratios he gives elsewhere. Faventinus (4) adds an informative note in his description of building a well, a passage that is clearly modeled on Vitruvius 8.6.14. He says that

> "although various authorities have instructed that two parts lime should be added to five parts sand, they have also shown that this formula will lead to renewed expenses later. A better formula has been found in which one part lime is mixed with two parts sand so that a greater initial expense provides a stronger bonding of the aggregate." (trans. author; based on Oleson 2014 and Plommer 1973).

Lime is clearly the more expensive of the two ingredients, presumably because of the processing required. Earlier in the passage, he defined the fine aggregate as *harena aspera*, so he must be speaking of *harena fossicia*. Faventinus never repeats Vitruvius's ratio of 1:3 for *harena fossicia*, so he seems to be providing a corrective to what the past authorities had recommended. Palladius (1.10) repeats Faventinus's advice to use one part lime with two parts sand leaving out any mention of Vitruvius's 2:5 ratio. Like Faventinus, he also suggests adding a third part of crushed terracotta if using river sand. This is yet another example where Palladius can be seen to be using Faventinus as his source rather than Vitruvius.

Water is not given as a component in the recipes, but the amount, the temperature, the purity, and the hardness or salinity of the water can all affect the quality of the mortar (Giuliani 2006: 220–21). Water is particularly important for hydraulic mortar because it is the critical catalyst for the chemical reaction to take place. Although the ancient authors do not give specific protocols, they seem to have understood the importance of water for the quality of the work. The earliest acknowledgement of the importance of water for hydraulic mortars comes at the end of the first century CE with Frontinus (*Aq*. 2.123), who notes that work on the aqueducts should occur between April and November to avoid freezing the mortar (*materia*) and that a hiatus should be taken in the hottest part of the summer because excessive heat also damages it. He does not say explicitly that the water is the central issue; however, his use of the verb *combibo* (to absorb) implies that it was understood that continuous moisture was important for the mortar to develop strength. Dio Cassius (48.51.4), writing over a century later, emphasizes the importance of water when describing the works of Agrippa around Lake Avernus. He notes that there is an earth (γῆ, *gē*) with special properties in the surrounding hills. After describing how the fire in the surrounding territory interacts with the earth to create those properties, he explains that the earth is heated and exposed to fire and then:

> "the masses of earth necessarily become porous and when exposed to the dry air crumble into dust. When this dust (κόνιν) is mixed with water and lime (κονία) they become a compact mass, and as long as they remain in the water they continue to set and harden" (trans. Oleson 2014).

This last comment touches on a critical aspect of all hydraulic mortar—the water is the catalyst for the reaction between the lime and the silica in the volcanic ash. It also reveals a greater understanding of the factors affecting the quality of the mortar than do the earlier writings.

Another substance used in place of water for making mortar and plaster was oil lees (*amurca*), which is the bitter, watery sediment left over from pressing olive oil. Columella (*Rust.* 1.6.12–13) recommends using it in constructing the floor of a granary. First one is to soak the soil thoroughly with *amurca* and then compact it by rolling or pounding before adding a *pavementum testaceum*. He then says to substitute *amurca* for water when mixing the lime and sand. The use of *amurca* in this case is intended as a type of herbicide and insecticide to keep away weeds, insects, and rodents (Cato, *Agr.* 128–129; Palladius 1.35).

Plaster

Plaster for covering walls or for making moldings was treated differently from structural mortar. The slaking of the lime was much more critical for plaster. It needed to be well slaked to remove any pieces of uncalcined quicklime that could destroy the smoothness and integrity of the surface over time. For the smoothest surfaces, particularly those that would be used as a base for fresco paint, marble dust was added to the final coats.

Latin terms used to refer to plaster coatings are more varied than the Greek κονιάμα (*koniáma*) and include *opus tectorium*, *opus albarium*, and *opus marmoratum*. *Opus tectorium* is a broad category of plaster work and can also include the floor material of a pond as indicated by Columella (*Rust.* 8.15.3), whereas *opus albarium* and *opus marmoratum* are types of *opus tectorium*. Varro (*Rust.* 1.57.2) refers to a special type of *opus tectorium* as "*opere tectorio marmorato*" and later simply as "*marmorato*" (*Rust.* 3.7.3). Vitruvius advises using the *marmoratum* when he is discussing wall painting on plaster, whereas *opus albarium* seems to refer more generally to white plastered walls and ceilings.

We saw earlier that Vitruvius (*De arch*. 7.2.2) gave a test for determining when lime was properly slaked for plasterwork (*opus albarium*)—the slaked lime must stick to the hoe like glue when it is withdrawn from the mixing pit. In Book 7, he gives another test for the proper mixing of *opus marmoratum* (*De arch*. 7.3.6)—the lime and marble dust should be mixed thoroughly with a trowel (*rutrum*) until the material no longer sticks when it is removed. Pliny (*HN* 36.177), drawing on Vitruvius, compares the two different tests saying explicitly that lime for *opus albarium* should stick to the mixing tool whereas that for *marmoratum* should not stick to it. Thus, the first test is for determining the proper consistency of the slaked lime before the fine aggregate is added, whereas the second test is for determining when the plaster is properly mixed after the marble dust has been added to the slaked lime. Neither author specifies the appropriate consistency for the plaster of slaked lime and sand.

Whitewash, a dilute mixture of lime and water, is another substance used by Roman builders for wall coverings. In the *Lex Puteolana* (2.16–20), whitewash is called *calx dealbata*. Vitruvius (*De arch*. 7.4.3) describes it more explicitly as "watered down lime" ("*calce ex aqua liquida dealbentur*"). In Faventinus's (24) version of this advice, he simply calls the whitewash "*liquid lime*" (*"calce liquida*"). In these passages, the authors are recommending using the whitewash to aid in the adhesion of a crushed terracotta and lime plaster (a type of *tectorium*) applied to fired brick as a means of waterproofing against moisture infiltration. They explain that the lime in the whitewash acts to adhere the crushed terracotta plaster to the brick.

Caulks and sealants

Quicklime and oil- or fat-based substances were often used in caulks intended to provide a waterproof seal. Vitruvius says to mix quicklime (*calx viva*) and olive oil into a paste for sealing between brick pavers and for sealing the segments of terracotta water pipes (*De arch*. 7.1.7, 8.6.8; followed by Faventinus 6, 19). Pliny (*HN* 36.181) says to slake freshly calcined quicklime in wine and then pound it together with pork fat (*adips suillus*) and fig (*ficus*) to create a type of caulk he calls *"maltha"*. Palladius (1.17) also advises the use of fats to waterproof a cistern—he says to rub the mortar floor and plastered walls with rich animal fat that has been boiled down (*"lardo pingui decocto*").

Concluding summary of key concepts

When using the ancient sources for information regarding the making of mortar, one cannot simply take a single translation in any of the modern languages as the "truth." As demonstrated in the previous discussions, there are many variables that can affect the information that comes down to us today. Best practices, especially for those depending on translation from the Greek or Latin, include the following:

- Always check multiple translations of a passage to get a sense of the breadth of possible interpretations. If one has philological training, one can compare the translations to the original Greek or Latin. Nevertheless, one must keep in mind that there is rarely an "original" text since most have been copied numerous times and different manuscripts may contain different words or phrases.
- Consider where the ancient author fits into the chronology of technical writing. For architecture, most later authors were depending on Vitruvius to some degree, and one finds much repetition of information between the writers. It is always worth understanding how an author has modified his predecessors and what sources he was using, as demonstrated by the examples given of Vitruvius, Faventinus, and Palladius and of Theophrastus and Pliny.
- Be mindful of the genre in which an author is writing and his overall intention in imparting the information to his readers. As discussed with the references of Seneca and Pliny to *pulvis puteolanus*, their goals in mentioning the topic in those passages are more rhetorical than technical. Another example of differing intentions is illustrated by Vitruvius and Faventinus, both writing architectural treatises. Vitruvius had much grander intentions than to impart technical knowledge to his readers. He was also trying to set the act of building into an overall conception of world order and to position his work among those of the great writers of the past (Courrént 2016; Callebat and Gros 1999). Faventinus had a different audience and intention in mind. He even says "Vitruvius Pollio has written eloquently and at length, and other authors with extraordinary knowledge. But for fear that their lengthy and erudite copiousness may frighten less aspiring

intellects off these studies, I have taken the resolution to clothe in everyday language a few items from their works, to be of use for private needs" (trans. Plommer 1973). Alternatively, Palladius was writing an agricultural treatise, so he too has his own agenda and audience different from his predecessors.

- Remember that many of the ancient technical terms used to discuss construction are ambiguous. The Latin term "*materia*" is a good example—it commonly refers to wood or ligneous matter (Vitr., *De arch* 2.9.1), but it can also have the more general meaning of "substance" and refer to mortar (Vitr., *De arch*. 2.5.1; Plin., *HN* 36.175). The only way to understand what such a term signifies is to look at the context in which it occurs and to compare it to other uses in similar contexts. The controversy over the meaning of *opus signinum* is a prime example of the problem that such linguistic ambiguity creates.

Finally, in the past centuries, the words of the ancient authors have often taken precedence over the material evidence, such that scientific approaches to the analysis of materials and techniques have been framed in terms of proving or disproving the information in the literary record. But as we have seen, written evidence has its own challenges and should not be taken as sacrosanct. Modern archaeometric studies allow the investigation into ancient building materials to go beyond what the ancient written sources tell us and can often provide much needed correctives to our understanding of actual construction practices in the ancient Mediterranean world.

Data availability All sources are published.

Declarations

Conflict of interests The authors declare no competing interests.

References

Aceto M (2021) The palette of organic colourants in wall paintings. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01392-3

Adam J-P (1994) Roman building: materials and techniques. Batsford, London

Arizzi A, Cultrone G (2021) Mortars and plasters – how to characterise hydraulic mortars. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01404-2

Ash HB (1934) Marcus Porcius Cato, on agriculture; Marcus Terentius Varro, on agriculture. Loeb Classical Library. Harvard University Press, Cambridge, Mass

Ash HB (1941) Lucius Junius Moderatus Columella, on agriculture. Loeb Classical Library. Harvard University Press, Cambridge, Mass

Bailey KC (1932) The Elder Pliny's chapters on chemical subjects, vol 2. Edward Arnold, London

Bartoldus J (2012) Palladius Rutilius Taurus Aemilianus: Welt und Wert spätrömischer Landwirtschaft. Wissner, Augsburg

Becker H (2021) Pigment nomenclature in the ancient Near East, Greece, and Rome. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01394-1

Bernárdez Gómez MJ, Guisado di Monti JC (2007) Las referencias al lapis specularis en la Historia Natural de Plinio El Viejo. Pallas:49–57

Blake ME (1947) Ancient Roman construction in Italy from the Prehistoric period to Augustus. Carnegie Institution of Washington, Washington

Boynton RS (1980) Chemistry and technology of lime and limestones. 2nd rev. edn. Wiley, New York

Braconi P (2009) Ostracus, asterico e lastrico. I pavimenti in cocciopesto degli antichi e l'opus signinum dei moderni. In: Angelelli C (ed) Atti del XIV Colloquio dell'Associazione italiana per lo studio e la conservazione del mosaico (Spoleto, 7–8 febbraio 2008). Tipografia Mancini, Tivoli, pp 371–83

Brandon CJ, Hohlfelder RL, Jackson MD, Oleson JP (2014) Building for eternity: the history and technology of Roman concrete engineering in the sea. Oxbow, Oxford

Buffone L, Lorenzoni S, Pallara M, Zanettin E (1999) Le macine rotatorie in rocce vulcaniche di Pompei. Rivista Di Studi Pompeiani 10:117–130

Burgio L (2021) Pigments, dyes and inks – their analysis on manuscripts, scrolls and papyri. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01403-3

Caley ER, Richards JFC (1956) Theophrastus, on stones. Ohio State University, Columbus, Ohio

Callebat L, Gros P (1999) Vitruve de l'architecture Livre II. Les Belles Lettres, Paris

Cam M-T (2001) Cetius Faventinus. Abrégé d'architecture privée. Collection des universités de France. Série latine 363. Les Belles Lettres, Paris

Caroselli M, Ruffolo SA, Piqué F (2021) Mortars and plasters – how to manage mortars and plasters conservation. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01409-x

Cavallo G, Riccardi MP (2021) Glass-based pigments in painting. Archaeological and Anthropological Sciences (forthcoming)

Chiotis E, Dimou E, Papadimitriou GD, Tzoutzopoulos S (2001) The study of some ancient and prehistoric plasters and watertight coatings from Greece. In: Aloupi E, Bassiakos Y, Facorellis Y (eds) Archaeometry issues in Greek prehistory and antiquity. Hellenic Society for Archaeometry and the Society of Messenean Archaeological Studies, Athens, pp 327–342

Ciapponi LA (1984) Fra Giocondo da Verona and his edition of Vitruvius. JWarb 47:72–90

Corso A, Romano E (1997) De architectura/Vitruvio. G. Einaudi, Turin

Courrént M (2016) Vitruve et les naturales quaestiones: La théorie de la matière dans le De Architectura. Arethusa 49:251–262

DeLaine J (2021) Production, transport and on-site organisation of Roman mortars and plasters. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01401-5

Domingo Sanz I, Chieli A (2021) Characterising the pigments and paints of prehistoric artists. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01397-y

Eckel EC (1907) Cements, limes, and plasters. Their materials, manufacture, and properties. 1st edn. Wiley, New York

Eichholz DE (1962) Pliny, natural history. Harvard University Press, Cambridge, Mass

Ergenç D, Fort R, Varas−Muriel MJ, Alvarez de Buergo M (2021) Mortars and plasters – how to characterise aerial mortars and plasters. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01398-x

Gargiani R (2013) Concrete from archeology to invention 1700–1769: the Renaissance of pozzolana and Roman construction techniques. École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
Giocondo G (1511) M. Vitruvius per Iucundum solito castigatior factus, cum figuris et tabula, ut iam legi et intelligi possit. G Taccuino, Venice
Giuliani CF (1992) Opus signinum e cocciopesto. In: DeRossi GM (ed) Segni I. Serie storia antica e archeologia 1, vol 1. Università degli Studi di Salerno, Napoli, pp 89–94
Giuliani CF (2006) L'edilizia nell'antichità. 2nd ed. rev. edn. Carocci, Rome
Gliozzo E (2021) Pigments – Mercury-based red (cinnabar-vermilion) and white (calomel) and their degradation products. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01402-4
Gliozzo E, Burgio L (2021) Pigments – Arsenic-based yellows and reds. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01431-z
Gliozzo E, Ionescu C (2021) Pigments – Lead-based whites, reds, yellows and oranges and their alteration phases. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01407-z
Gliozzo E, Pizzo A, La Russa MF (2021) Mortars, plasters and pigments – Research questions and sampling criteria. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01393-2
Goodman MM (1989) The effects of woodash additive on the structural properties of lime plaster. M.Sc., University of Pennsylvania
Grandi Carletti M (2001) Opus signinum and cocciopesto. Alcune osservazioni terminologiche. In: Atti del colloquio dell'associazione italiana per lo studio e la conservazione del mosaico, Pompeii 22–25 marzo 2000. Edizioni del girasole, Ravenna, pp 183–97
Granger F (1933) Vitruvius, On architecture. vol 1. Loeb Classical Library. Harvard University Press, Cambridge, Mass
Granger F (1935) Vitruvius, On architecture. vol 2. Loeb Classical Library. Harvard University Press, Cambridge, Mass
Gros P (2003) L'*opus signinum* selon Vitruve et dans la terminologie archéologique contemporaine. In: Ciotta G (ed) Vitruvio nella cultura architettonica antica, medievale e moderna. Atti del convegno internazionale di Genova, 5–8 novembre 2001. De Ferrari, Genova, pp 142–52
Gros P (2015) Fra Giocondo lecteur et interprète de Vitruve. La valeur de sa méthode et les limites de sa logique. Monuments Et Mémoires Fondation Eugène Piot 94:201–241
Guarnieri C, Lugli S, Gullì D, Pisapia MS, Ingravallo V (2015) Il lapis specularis a Pompei ed Ercolano. Riv Stud Pompeiani 26–27:142–5
Healy JF (1999) Pliny the Elder on science and technology. Oxford University Press, Oxford
Hellman M-C (1999) Choix d'inscriptions architecturales grecques. Maison de l'Orient Méditerranéen, Lyon
Jackson MD, Marra F, Deocampo D, Vella A, Kosso C, Hay R (2007) Geological observations of excavated sand (harenae fossiciae) used as fine aggregate in Roman pozzolanic mortars. JRA 20:25–53
Knapp CW, Christidis GE, Venieri D, Gounaki I, Gibney-Vamvakari J, Stillings M, Photos-Jones E (2021) The ecology and bioactivity of some Greco-Roman medicinal minerals: the case of Melos earth pigments. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01396-z
La Russa MF, Ruffolo SA (2021) Mortars and plasters - how to characterise mortars and plasters degradation. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01405-1
Lamprecht H-O (1984) Opus caementicium: Bautechnik der Römer. Beton-Verlag, Düsseldorf
Lancaster LC (2015) Innovative vaulted construction in the architecture of the Roman Empire: 1st to 4th centuries CE. Cambridge University Press, Cambridge
Lancaster LC (2019) Pozzolans in mortar in the Roman empire: an overview and thoughts on future work. In: Ortega IF, Bouffier S (eds) Mortiers et hydraulique en Méditerranée antique. Publications Universite Provence, pp 31–9
Lancaster LC, Sottili G, Marra F, Ventura G (2010) Provenancing of lightweight volcanic stones used in ancient Roman concrete vaulting: evidence from Turkey and Tunisia. Archaeometry 52:949–969
Livadiotti M (2006) Note preliminari sulle techniche costruttive di Coo in età ellenistica e romana. In: Adembri B (ed) Aeimnestos: miscellanea di studi per Mairo Cristofani. Centro Di, Florence, pp 178–87
Lugli G (1957) La tecnica edilizia romana con particolare riguardo a Roma e Lazio. G. Bardi, Rome
Marra F, Anzidei M, Benini A, D'Ambrosio E, Gaeta M, Ventura G, Cavallo A (2016) Petro-chemical features and source areas of volcanic aggregates used in ancient Roman maritime concretes. J Volcanol Geoth Res 328:59–69
Martin, R (1965) Manuel d'architecture grecque. vol. 1, Matériaux et techniques. J Picard, Paris
Martin R, Guiraud C (1976) Traité d'agriculture. Palladius. Les Belles lettres, Paris
Massazza F, Costa U (1977) Factors determining the development of mechanical strength in lime–pozzolana pastes. In: Schneider L (ed) Proceedings of the XII conference on silicate industry and silicate science, vol. 1. SILICONF, Budapest, pp 537–52
Mastrotheodoros GP, Beltsios KG, Bassiakos Y (2021) Pigments – iron-based red, yellow and brown ochres. Archaeological and Anthropological Sciences (forthcoming)
Merriman M (1920) American civil engineers' handbook. 4th ed. rev. edn. Wiley, New York
Murat Z (2021) Wall paintings through the ages. The medieval period (Italy, 12th-15th century). Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01410-4
Ohl RT (1928) The Enigmas of Symphosius. Philadelphia
Oleson JP (2014) Ancient literary sources concerned with Roman concrete technology. In: Brandon CJ, Hohlfelder RL, Jackson MD, Oleson JP (eds) Building for eternity: The history and technology of Roman concrete engineering in the sea. Oxbow, Oxford, pp 11–36
Orlandos AK (1966–68) Les matériaux de construction et la technique architecturale des anciens grecs. vols. 1–2. E. de Boccard, Paris
Owen T (1807) The fourteen books of Palladius Rutilius Taurus Aemilianus, on Agriculture. J White, London
Peacock DPS (1980) The Roman millstone trade: a petrological sketch. WorldArch 12:43–53
Pérez-Arantegui J (2021) Not only wall paintings – pigments for cosmetics. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01399-w
Plommer H (1973) Vitruvius and later Roman building manuals. Cambridge Classical Studies. Cambridge University Press, Cambridge
Rose V (1899) Vitruvii de architectura libri decem. Teubner, Leipzig
Rowland ID (2011) The Fra Giocondo Vitruvius at 500 (1511–2011). JSAH 70:285–289
Rowland ID, Howe T (1999) Vitruvius: ten books on architecture. Cambridge University Press, Cambridge
Russell B, Fentress E (2016) Mud brick and pisé de terre between Punic and Roman. In: DeLaine J, Camporeale S, Pizzo A (eds) Archaeology of construction V. Man-made materials, engineering, and infrastructure, Proceedings of the conference, Oxford April 11–12, 2015. Consejo Superior de Investigaciones Científicas, Mérida, pp 131–43

Rykwert J, Leach N, Tavernor R (1988) Alberti. On the art of building in ten books. MIT Press, Cambridge, Mass

Salvadori M, Sbrolli C (2021) Wall paintings through the ages. The Roman period: Republic and early Empire. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01411-3

Švarcová S, Hradil D, Hradilová J, Čermáková Z (2021) Pigments – copper-based greens and blues. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01406-0

Ungaro L, Giusberti P, Rava A, Prisco L (1993) Emiciclo dei Mercati Traianei. Intervento di restauro delle cortine laterizie. BCom 95.2:181–99

Vitti P (2021) Mortars and masonry - Structural lime and gypsum mortars in antiquity and middle ages. Archaeological and Anthropological Sciences. https://doi.org/10.1007/s12520-021-01408-y

Wiss JE, Camp TP, Ladoo RB (1930) Gypsum plaster in the ceramic industries. J Am Ceram Soc 13:287–314

Lancaster LC (2012) Ash mortar and vaulting tubes: Agricultural production and the building industry in North Africa In: Camporeale S, Dessales H, Pizzo A (eds) Arqueología de la construcción: los procesos constructivos en el mundo romano: La economía de las obras (Paris, Ecole Normale Supérieure, 10-11 décembre 2009). Madrid, pp 145–60