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Pozzolans in Mortar in the Roman Empire: An Overview and Thoughts on Future Work

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Summary – This paper focuses on three different ingredients used to create hydraulic mortar: volcanic ash, crushed terracotta, and plant ash. Each one imparts somewhat different characteristics to the mortar and has a different processing method, which would have affected the *chaîne opératoire* of the building site. One goal is to examine these characteristics and processes. A second goal is to examine some problems in the terminology used to identify the ingredients. How can choices in terminology, such as "crushed tile mortar" vs. "crushed terracotta mortar" or "mortar with charcoal" vs. "mortar with ash", affect our understanding of the significance of choices made by ancient builder? I argue that using precise and objective terms to describe the ingredients in the mortar is an important step in being able to determine source materials, which in turn can provide insight into organizational practices on the worksite.

Résumé – Cet article est consacré à trois ingrédients différents utilisés dans la confection du mortier hydraulique : cendre volcanique, terre cuite broyée, et cendre végétale. Chacun d'entre eux confère des caractéristiques quelque peu différentes au mortier et implique des procédés de traitement différents, qui ont pu affecter la chaîne opératoire du chantier. Le premier objectif de l'article est d'analyser ces caractéristiques et procédés. Le deuxième est d'examiner certains problèmes qu'implique l'usage de tel ou tel mot pour identifier les ingrédients. Comment les choix terminologiques tels que « mortier de tuileau » ou « mortier de terre cuite écrasée », « mortier de charbon » ou « mortier de cendres » influencent-ils notre compréhension sur le sens des choix faits par le constructeur de l'Antiquité ? Selon l'auteur, l'utilisation de termes précis et objectifs pour décrire les ingrédients du mortier est une étape importante dans la capacité de déterminer les matériaux de base, ce qui par conséquent peut fournir un aperçu des pratiques organisationnelles du chantier.

In this paper, I focus on some of the archaeological implications of studying mortar, especially structural mortar. I use the term "pozzolan" (as opposed to "pozzolana") to indicate an ingredient that reacts with lime to create a hydraulic mortar. Hydraulic mortar was important for building harbors and for waterproofing floors, roofs, and liquid containment structures; however, the more important properties for structural mortars in terrestrial constructions are the greater strength and quicker curing times, which can affect both the design and timetable of the project. I examine three different types of pozzolans: volcanic ash, crushed terracotta, and plant ash (Fig. 1). All three have the potential to contain enough soluble silica to react with lime to create calcium silicate hydrate (C-S-H), which is the main component, along with alumina, that gives lime mortar its added strength and the ability to harden under water.[1]

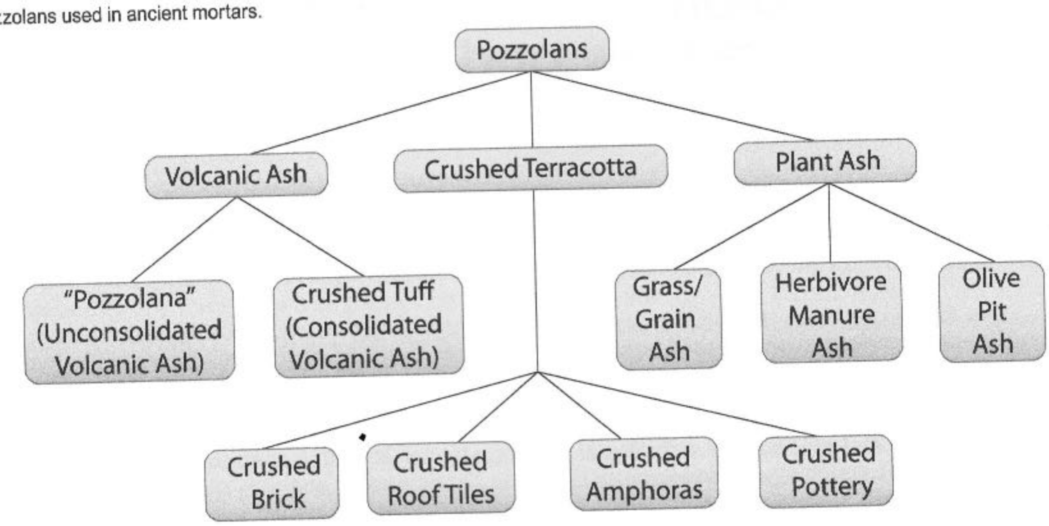
Volcanic Ash

Volcanic ash has long been used to create hydraulic mortar, and it is often called "pozzolana", which is a modern builder's term for unconsolidated volcanic ash that reacts with lime. A second, less recognized source comes from volcanic tuff, which is basically a consolidated form of volcanic ash. Both types of volcanic ash are available in many areas within the Mediterranean. The most famous comes from the Bay of Naples. Pliny the Elder (*HN* 35.167) called it *Puteolanus pulvis*, or powder from Puteoli (modern Pozzuoli from where we get "pozzolana"). Vitruvius (*De arch.* 2.6.1) noted that it was particularly effective for making lime mortar that sets underwater but also that it improved mortar for structures on land. Nevertheless, he recognized that around Rome, *harena fossicia* (also a type of unconsolidated volcanic ash) made better mortar than river or sea sand (*De arch.* 2.4), although he did not recommend it for underwater construction. Therefore, Vitruvius did not see the two substances as the same, but he recognized that both could improve the quality of structural mortar. That Roman builders prized the *Puteolanus pulvis* from the Bay of Naples for underwater structures is supported by the results of the Roman Maritime Concrete Study (ROMACONS). Analyses of mortar from cores of a number of different harbor installations around the Mediterranean suggest that the *Puteolanus pulvis* from the Bay of Naples was exported specifically for underwater harbor construction.[2]

1 For an overview of the various pozzolans used with lime mortar, see Coutelas 2009: 19-21.

2 Determining the source of volcanic ash with absolute certainty is not currently possible, but the mineralogical components and the immobile trace element ratios of the mortars in the ROMACONS study are most similar to the volcanic products from the Bay of Naples and are completely different from other major volcanic sources, such as the Aeolian islands and the volcanic Aegean islands of Santorini, Melos, and Nisyros (Brandon *et al.* 2014: 153-159).

Fig. 1 – Chart of pozzolans used in ancient mortars.



For terrestrial structures, Roman builders outside of Italy sometimes used their own locally available volcanic ash to make mortar, even if it was not necessarily as reactive as the Italian products. One well-known source of volcanic ash used as a pozzolan in modern times occurs along the Rhine in the Eiffel region of Germany (Fig. 2). The ash comes in both unconsolidated form, called *Tuffasche*, and the more reactive and consolidated trass, which is a type of tuff. The difference in reactivity between the two is apparently due to the higher zeolitic content of the trass, which came about during alteration from weathering.[3] The trass had to be crushed or ground before it was added to the mortar, and by the 18th century elaborate grinding machines had been invented because it was a major export commodity for the Netherlands (where the German trass was processed).[4] Some evidence suggests that Roman builders along the Rhine were also using this ash. Various ancient monuments in Cologne were built with mortar containing volcanic ash. H.-O. Lamprecht,[5] who published these mortars in 1984, assumed that the ash was probably the local trass but did not conduct chemical or mineralogical analyses. If the volcanic ash was in fact local, one wonders whether the builders in Cologne used the less reactive but easier to quarry *Tuffasche* or the higher quality ground tuff. Ancient Builders were not averse to grinding tuff when necessary as shown further east where mortars with ground tuff have been found at Pergamum[6] and Sagalassos,[7] both of which are in or near volcanic zones.

Crushed Terracotta Mortar

As is well known, the standard Roman method of creating hydraulic mortar for waterproof flooring and revetments was to add crushed terracotta to lime mortar, but Vitruvius (*De arch.* 5.2.1) also recommends crushed and sifted terracotta (*testa tunsam et succretam*) for improving structural mortar when *harena fossicia* was not available. Like volcanic ash, terracotta can contain high levels of silica and alumina, which upon firing become soluble in water and can combine with lime. A number of factors can affect the reactivity of the terracotta including type of clay, grain size, and firing temperature. The two most common types of clay used by Roman craftsmen are illitic and kaolonitic. Most Roman bricks, tiles, amphoras and pots are made with illitic clay, but some cookware is made with kaolonitic clay because of its greater resistance to thermal shock.[8] The different clays become reactive at different firing temperatures and produce different levels of compressive strength in mortars. Results of one study showed that mortar made with illitic clay started to gain strength when the firing temperature of the clay reached 650 °C, and strength was optimized at a firing temperature of 930 °C.[9] In the same study, mortar made with kaolonitic clay was optimized at the lower temperature of 650 °C.[10] Kaolinitic clay is actually a much better pozzolan than illitic clay and produces higher compressive strength.[11] For both clays, once vitrification occurs, they lose their reactivity.[12]

3 Massazza, Costa 1977.

4 Gargiani 2013: 62-76.

5 Lamprecht 1984: 46-49.

6 Brinker, Garbrecht 2007: 100.

7 Callebaut *et al.* 2000; Degryse *et al.* 2002.

8 Cuomo di Caprio 2007: 137-140.

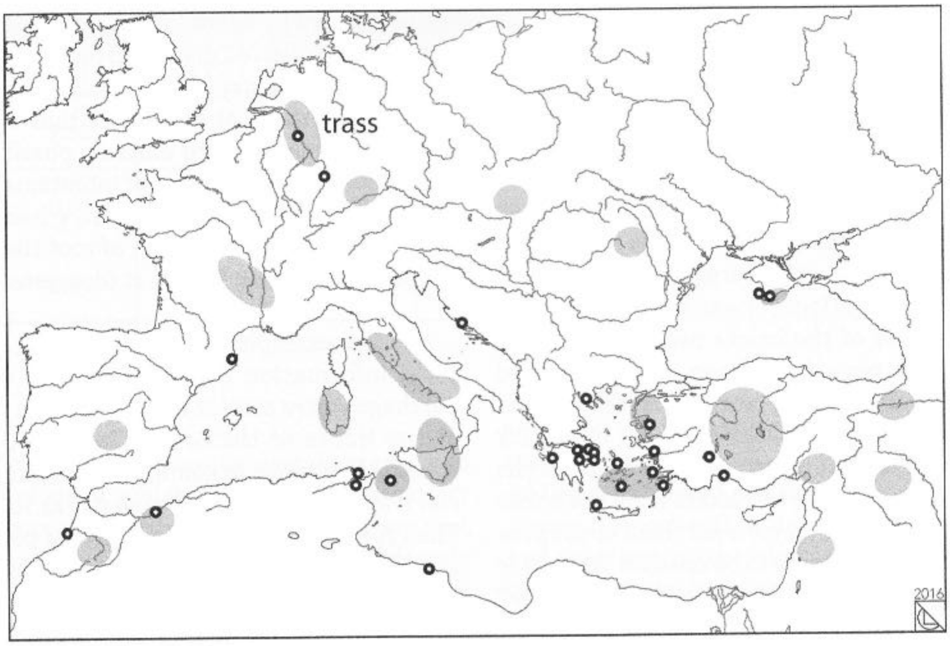
9 The upper firing limit for illitic clay to remain reactive is more commonly cited as 900 °C (e.g., Baronio, Binda 1997; Massazza 1998: 485).

10 He *et al.* 1995: 1696.

11 Chakchouk *et al.* 2006.

12 Over-fired terracotta can be determined by simple examination under an optical microscope. Under polarizing light the over-fired ceramic appears black whereas the unvitrified ceramic appears luminous red with visible crystals. I thank Ruth Siddall for pointing this out at the conference.

Fig. 2 – Map showing locations of mortar containing volcanic ash. Gray areas denote volcanic zones. For a list of locations, Lancaster 2015: WebCat 2A (online content) at www.cambridge.org/vaulting.

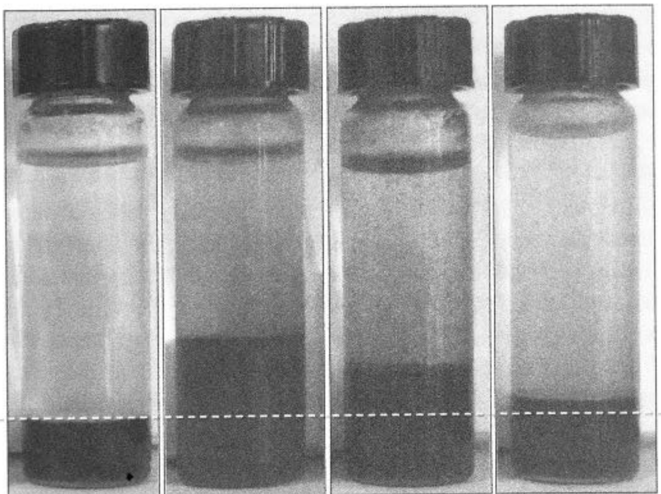


The choice of source material can be an important factor in creating a good quality hydraulic mortar. For example, terra sigillata fine ware fired above 1050 °C would not have reacted with the lime, nor would have over-fired wasters, whereas bricks, tiles, amphoras and coarse ware, which are typically fired closer to 800-900 °C, would have been good choices. Cookware made of kaolonitic clay has the potential to be a very good pozzolan.

A very simple test for determining the reactivity of a potential pozzolan is given by A. D. Cowper in his book, *Lime and Lime Mortar* (1927). He instructs the reader to add 0.5 gm of the powdered pozzolan to 0.3 gm of slaked lime in a small bottle, to cover it with a few centimeters of water, and then to shake the bottle every 12 hours for a week. He explains that if the reaction is occurring then the substance in the bottle will grow as more lime reacts with the pozzolana because the hydrates created are much bulkier than either the lime or the pozzolan.[13] To test this test, I obtained powdered red illitic clay from the art studio at my university and had it fired at different temperatures. In figure 3, one can see that after five days the clay fired at 720 °C was quite reactive and the bulk had increased significantly, but the clay fired at 980 °C was much less reactive. By 1150 °C there was very little activity at all. I return to this "shake test" in the last section.

One of the themes that developed during the conference was the importance (and the problems) of terminology both within single languages and across different languages.

Fig. 3 – Results of «shake test» after 5 days using illitic clay (red art clay powder) fired at different temperatures.



Mortar made with crushed terracotta has often been called by the ancient Latin term "*opus signinum*", which has commonly been used synonymously with "*cocciopesto*", the Italian term for revetment mortar of crushed terracotta. C. F. Giuliani has argued that *opus signinum* did not refer to crushed terracotta mortar but rather to a method of wall construction, whereas P. Gros provided a counterargument to Giuliani focusing on the problematic interpretation of Vitruvius's passage due to the emendations that have occurred in the transcriptions of the Vitruvian manuscripts.[14] Given the debates surrounding

13 Cowper 1927: 48-49.

14 Giuliani 1992; Gros 2003.

the ancient meaning of *opus signinum*,[15] recent scholars have advised avoiding it completely as a descriptive term for mortar.[16]

I have opted to use the generic "crushed terracotta mortar" because it does not imply a particular class of source material or type of application, though "crushed ceramic mortar" is equally generic. Using more specific terminology, such as "crushed tile mortar", or the French "*mortier à tuileaux*" can give a false impression if the mortar was actually made using crushed pottery or amphoras. The terminology used can have an impact on interpretation. For example, in a project comparing the properties of the bricks used to construct domes in the Ottoman period to those of the crushed terracotta aggregate in the binding mortar, the researchers referred to the pozzolan as "crushed brick" or "brick powder".[17] They found that the terracotta aggregate in the mortar was more reactive than the terracotta from the bricks used in the construction, which in turn led them to propose that the builders chose special bricks to be crushed for mortar aggregate. However, if one allows that the "brick powder" could have been made from a different class of terracotta object, such as amphoras or pottery, then the broader implications are quite different – instead of choosing or even creating special bricks to grind, the Ottoman builders could have been using recycled material that was easier and cheaper to obtain and to crush.[18] The words we use inevitably conjure images in the mind, which in turn can affect the way we think about the results. Thus using a more generic terminology can help maintain objectivity as one formulates an interpretation.

Alternatively, when the source material of the terracotta in a mortar can be identified more precisely, using the appropriate terminology can open windows onto broader organizational issues. This is especially clear when applying the *chaîne operatoire* approach in which the step-by-step processes of production are identified in an attempt to understand better the social and economic factors at play.[19] For example, R. Siddall[20] studied both structural and revetment mortars from baths at ancient Corinth and determined that when terracotta was used, it consisted mainly of crushed cookware and amphoras rather than brick. Moreover, she noted that the ceramic fabrics were a reddish color, as opposed to the local buff colored fabrics, and contained mineral assemblages that indicated the wares were largely imported. After presenting calculations for the vast amount of crushed terracotta required for the baths, she hypothesizes the existence of depots that collected discarded terracotta objects for reuse in the building industry, which in turn would suggest some sort of central control. At a port city that was a center of trade, such arrangements are entirely possible – witness Monte Testaccio in Rome. The idea of intentional collection of refuse for reuse in the building industry has been suggested for Pompeii,[21] and the collection of roof tiles for reuse has been proposed for Roman Britain at Gloucester.[22]

Another example of how identifying source material can yield information beyond technical details comes from Carthage where mortar floor fragments found in excavations at the House of the Greek Charioteers were reported to contain fragments of commonware identifiable by fabric and rim fragments. Some had burn marks suggesting cookware.[23] The types of mortar with terracotta pieces large enough to identify came from a sealed context providing a *terminus ante quem* of the early to mid 1st century AD, and are likely to be from Punic household contexts earlier than the 146 BC Roman destruction. Similar studies of the early datable examples of this type of floor mortar could provide further insight into how the source material was acquired during the early development of the technique.

For both terracotta and volcanic tuff, crushing and grinding were necessary to obtain the fine grain sizes that increase the surface area and the reactivity of the pozzolan. We have no direct evidence for how the materials were processed, but we can look for parallels in the mining industry where ores had to be crushed. Numerous examples of anvil stones have been found together with grinding stones at gold and silver mines in Wales and northern Spain and Portugal.[24] The anvil stones bear evenly spaced cup-shaped depressions where hammers hit, and Lewis[25] has argued that they were part of a water-powered mechanism, such as the water powered grain-hulling machine described by Pliny the Elder (*HN* 18.97). We do know that water powered mechanical marble saws were used by the 3rd century AD.[26] So, the technology to crush and grind tuff and terracotta by mechanical means existed, but as yet no archaeological or literary evidence exists to indicate if it was employed for this purpose.

15 For a review see Braconi 2009.

16 e.g., Tang 2006: 100-102.

17 Böke *et al.* 2006.

18 A thesis project, directed by the lead author, H. Böke, on the Roman and Byzantine period bricks and mortar of the Serapeum at Pergamum yielded similar differences between the reactivity of the terracotta aggregate in the Byzantine mortar and that of the Byzantine wall bricks (Aslan Özkaya 2005).

19 Miller 2007: 29-30.

20 Siddall 2011.

21 Dicus 2014: 61-62.

22 Warry 2017: 84-89.

23 Dunbabin 1978: 180.

24 Burnham, Burnham 2004: 281-284.

25 Lewis 1997: 106-110.

26 Ritti *et al.* 2007.

Fig. 4 – Major constituents (%) of various organic ashes. Wheat straw, olive stones, olive press cake and poplar wood (Thompson 2008: 48, 54). Rye straw, lawn grass, oak wood, and pinewood (Rogers 1991: 26).

	Wheat straw	Rye straw	Lawn grass	Olive stones	Olive press cake	Oak wood	Pine wood	Poplar wood
Silica SiO_2	55.32	49.27	39.64	30.82	21.20	15.30	10.00	5.90
Alumina Al_2O_3	1.88		16.60	8.84	2.90	0.13	0.43	0.84
Iron oxide Fe_2O_3	0.73	1.91	3.44	6.58	2.70	2.40	4.00	1.40
Calcium Oxide CaO	6.14	8.20	12.88	14.66	13.80	30.02	25.00	49.92

Plant Ash

Like the clay used for Roman terracotta, certain plants also contain high levels of silica, which when burned, can react with lime. The primary sources of high-silica ash are fast growing annual plants such as grasses, grains, and cereals like rice and wheat.[27] Other sources, such as olive pits or olive pressings, produce ash with moderate amounts of silica. Most tree woods produce ash with very little silica, though the bark often has higher amounts than the wood (Fig. 4). In some areas, mortars are often reported as containing charcoal, so it is worth emphasizing the importance of distinguishing between charcoal and ash, because chemically they are different. Charcoal is formed by the imperfect combustion of organic material, which results in a substance consisting mainly of carbon, whereas ash is the completely burnt remains of organic material consisting of mineral remains, among which can be silica. Thus charcoal does not react with lime but some types of ashes do. Charcoal pieces are larger than ash particles and are therefore more easily identified. Also, ash can be more difficult to identify if it has been entirely consumed when it was converted into calcium silica hydrate. The important point is that when charcoal is present, a certain amount of ash probably accompanied it. The charcoal can act as an indicator for the presence of ash, but it is not the pozzolan itself. I point this out because there has been confusion in the literature. For example, this quote is taken from an article in a peer-reviewed scientific journal: "This mortar contains abundant, evenly distributed charcoal suggesting that, in this case, the fuel was deliberately added to the mortar as a pozzolan. However, no references were found in Roman records concerning the addition of charcoal as a pozzolan."[28] In this case, if there was a pozzolanic reaction detected, the pozzolan was likely the ash that accompanied the charcoal rather than the charcoal itself.

Non-reactive ash can also provide beneficial qualities to mortars, particularly for revetment mortars. One thesis project studied the effects of non-reactive ash on mortar by adding inert wood ash from oak, ash and beech (with the charcoal sifted out) to lime mortar in different proportions and then testing the mortars. The results indicated that at 10-20 % ash the benefits included greater speed in the set of the mortar, greater water retention, reduced cracking, and increased flexural strength. However, once the proportion of ash reached 30 % these benefits were lost.[29] These qualities of greater set speed and increased flexural strength are important for revetment mortars, especially the base coat, but for structural mortar, the more critical properties are compressive strength and curing time, which are those that reactive ash could potentially impart.

If builders were adding reactive plant ash to mortar, where did they acquire it? As with the source material for terracotta, the answer could provide insight into broader organizational and economic issues. One possibility is they collected the ashes from field burning. Both Virgil (*Georgics* 1.84) and Pliny the Elder (*HN* 18.300) mention this practice as a means of killing weeds between crops; however, the gathering of the ash over broad swaths of land would not have been very efficient. More likely is that they collected ashes from more discrete locations, such as kilns and home hearths. We also know that farmers intentionally created ashes from manure patties. Pliny (*HN* 17.49) notes that north of the Po valley they used animal manure ash to condition the soil. Herbivores, such as equines, cattle, sheep, and goats, eat various types of grasses and cereals and produce manure with high levels of silica. In fact, results from recent studies indicate that the ashes from feedlot waste can act an effective substitute for Portland cement in concrete.[30]

27 Biricik *et al.* 1999; Rogers 1991.

28 Pavía, Caro 2008: 1810; Elsen *et al.* 2012: 133 also name charcoal as a pozzolan (citing Pavía, Caro 2008).

29 Goodman 1989.

30 Şahin *et al.* 2006; Bellizia *et al.* 2002; Lancaster 2015: 27-29.

Fig. 5 – Graph showing results of «shake test» of various types of plant ashes: horse manure, sheep manure, wheat, grass, branches with bark, and pinewood.

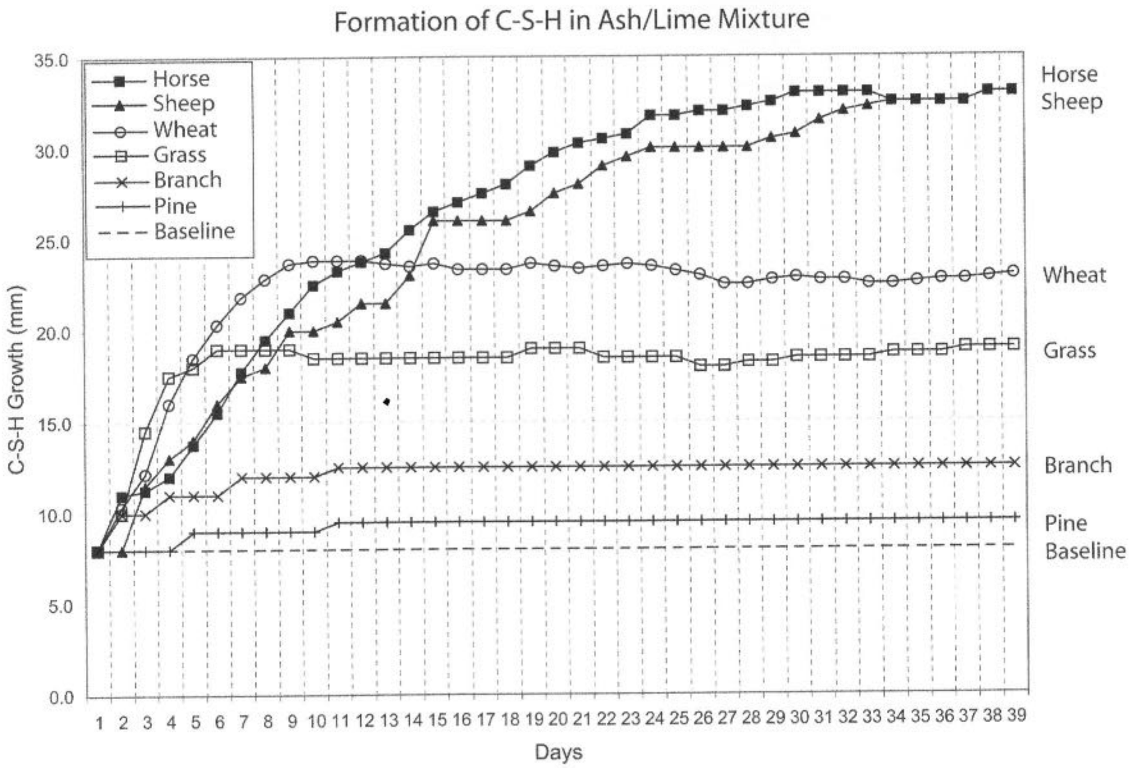
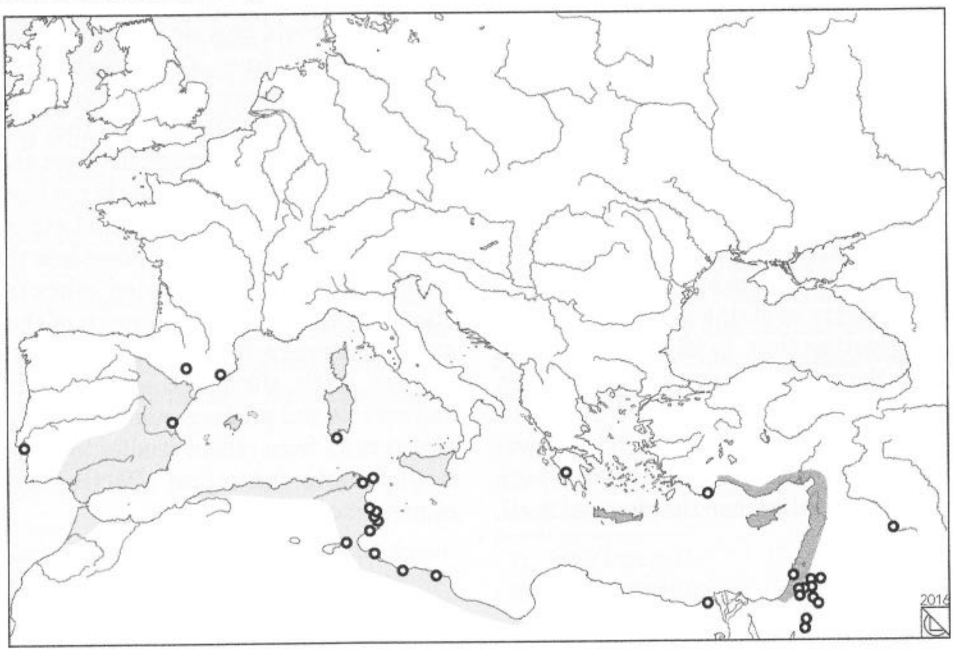


Fig. 6 – Map showing locations of mortar with ash. Dark gray denotes areas of Phoenician influence and light gray denotes areas of Punic influence. For a list of locations, Lancaster 2015: WebCat 2C (online content) at www.cambridge.org/vaulting.



To compare the efficacy of various types of ashes, I employed Cowper's shake test, described earlier. The results, shown in figure 5, indicate that the grass and wheat ash reacted quickly, but ultimately they did not convert as much lime into C-S-H as did the manure ashes, which reacted more slowly but ultimately created much more C-S-H. The horse manure ash was somewhat quicker to react than the sheep manure ash, but after 38 days both had converted similar amounts of lime into C-S-H. As expected, the wood ash did not display much reactivity at all, but the presence of bark did increase the amount of C-S-H minimally.[31]

The distribution of plant ash mortar (Fig. 6) is focused mainly in the Levant and in North Africa, southern Spain, Pantelleria, and Sardinia, which were all areas under Phoenician or Punic influence at some point. Theophrastus (*On Stones* 69), writing in the late 4th century BC, provides a clue that may help explain this pattern when he says:

Gypsos is also burnt in Phoenicia and in Syria, where it is fired in a furnace. Marbles especially are burnt, and also the more ordinary kinds of stones, while cow manure is placed alongside the hardest ones to make them burn better and more quickly.[32]

Thus this practice of using manure as fuel may have led to the discovery that the ashes from the limekiln (and elsewhere) could create a hydraulic mortar, and this knowledge could have then spread from Phoenicia to the west via colonization and later via Punic expansion.

Evidence from Carthage suggests that the use of plant ash in mortar for lining cisterns was a Punic technique. In a cistern under the House of the Greek Charioteers, the excavators found two phases of coatings. The original coating consisted of 4 cm layer of mortar containing 5-10 % burnt organic material (source material not determined). This layer was underneath a later mortar coating containing 30-40 % volcanic material but no organic ash. The earlier mortar was very similar to other Punic cisterns at Byrsa, which also contained minor amounts of organic ash, and was therefore considered to be pre-Roman.[33] With regard to the volcanic ash in the later coating, the results reveal that volcanic ash was imported given that there are no volcanic materials in Tunisia. The source of the volcanic ash was not determined, but the most likely candidates are Sardinia, Sicily, or Pantelleria.[34]

Interestingly, in Tunisia the practice of adding plant ash to lime mortar continued into modern times. In Tunis during the 18th century, the traveller Thomas Shaw wrote that he had seen builders mix a third part wood ash with lime and sand for building arches, cisterns, and terraces on top of their houses.[35] Whether his use of the term "wood ash" literally meant ash from wood alone is unclear. As we saw earlier, non-reactive ash is only beneficial when added in small amounts (10-20 %), so adding a third part non-reactive ash would have been of little benefit, whereas if the ash were reactive it could have imparted some added strength to the mortar. Here is a clear example of how a more generic term, like "plant ash" would be appropriate (unless it really was ash from wood alone). This example also emphasizes how a study of the effects of reactive ash in mortar, which would complement the study of non-reactive ash,[36] discussed above, could yield useful insights into the choices of builders.

As with the crushed terracotta in mortar, determining the source material of plant ash is not always possible. The best indicator comes from the identification of the charcoal that accompanies it. For example, the lining of the Roman aqueduct at Caesarea contains remains of charred wood pieces along with high-silica remains of stems and seed husks.[37] A majority of the examples of plant ash mortar shown in figure 5 come from the linings of baths or liquid containment structures, but a few come from structural mortars as well. At Carthage, the structural mortars from walls in the House of the Greek Charioteers contained various types of plant remains. The most common were olive pits, but other types of plants were also found including wheat, barley, rye, canary grass, and figs, all of which contain large amounts of silica.[38] Most of these identifiable components are carbonized remains, but again their presence acts as a marker indicating the likelihood of high-silica ash. In Alexandria, the substructure vaults of the late 4th century AD bath at Kom el Dikka also contain mortar with ash from straw and reeds,[39] both of which contain high levels of silica. One wonders if the remains of straw and reeds could have been from manure used as fuel, which was very common in Egypt. In fact, dried manure was traded as a commodity from the Pharaonic period until at least the 2nd century AD, when it was subject to an import tax and sold as a market item around the Temple of Serapis at Oxyrhynchus, as recorded on a papyrus found there.[40] The mortar of the superstructure of the bath at Kom el Dikka was

31 See further, Lancaster 2012.

32 The word indicating the cow manure (βόλιτον) on the existing Greek manuscripts is not preserved, but Pliny the Elder (*HN* 36.182) took his account of calcining stones directly from Theophrastus and supplies the missing words (in Latin) as *fimo bubulo* (Caley, Richards 1956: 220-221).

33 Davis, Humphrey 1981: 46-47.

34 The volcanic component was described as consisting of "pieces of mafic, aphanitic basalt with euhedral plagioclase and pyroxene" (Davis, Humphrey 1981: 45 n. 4). For importation of lightweight volcanic scoria into Carthage from Sardinia, see Lancaster *et al.* 2010.

35 Gargiani 2013: 18.

36 Goodman 1989.

37 Goodman 1989.

38 Ford, Miller 1978.

39 Kolataj 1992: 85, 176.

40 Rea 1982.

made with crushed terracotta mortar (personal observation), which raises the question as to why the ash mortar was used in the substructures. Further analysis of mortar samples from the structure could yield answers.

Ultimately, I doubt that plant ash ever became an important additive in structural mortar, but it did become common in some areas, especially for revetment mortars. Moreover, after reading many mortar reports, I have come to realize the importance of distinguishing between charcoal and ash in describing hydraulic mortar. The ashes and charcoal may well have been secondary materials from the lime kiln in some cases, as many have proposed, but I do think at some point in antiquity the builders began to add plant ash intentionally, as they were clearly doing in 18th century Tunis. •

In this brief overview, my goal has been to illustrate how using appropriate terminology and noting precisely the pozzolans within the mortar with attention to source materials can provide important information for the broader understanding of the economics within a city or region. During the course of the discussions, I have also pointed to a number of questions and potential projects as examples of ways in which mortar analyses can be framed to be of use to the archaeologist and historian as well as to the scientist and conservator.

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