How Did Expertise in Maritime Hydraulic Concrete Spread through the Roman Empire?

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Abstract The long passage in Vitruvius’ De architectura concerning the methods and materials for building concrete harbour structures in the sea (5.12.2-5) is unique in ancient literature and consequently frequently cited by modern scholars. Less well known are passages elsewhere in Vitruvius that deal with hydraulic concrete in marine structures, and similar comments in the works of Strabo, Pliny the Elder, Seneca, Suetonius, and Dio Cassius. These authors all comment on the need for a crucial ingredient, pulvis puteolanus volcanic ash from the region around ancient Puteoli on the Bay of Naples. None of these passages, however, concern engineering works outside central Italy, although the ROMACONS Project has documented the use of pulvis puteolanus (now popularly called pozzolana) in Roman harbour structures throughout the Mediterranean. It seems likely that information concerning the ideal materials for placing hydraulic concrete, and their ratios, was spread not only by the movement of central Italian engineers around the Mediterranean but also by the circulation of sub-literary engineering manuals.

Introduction: Roman Maritime Concrete

Since 2001 Oleson, in collaboration with Christopher Brandon and Robert Hohlfelder, has co-directed the Roman Maritime Concrete Study (ROMACONS), collecting 36 large diameter cores from numerous maritime structures at 10 Roman harbour sites in Italy, Israel, Egypt, Greece, and Turkey [4, 8, 12, 18, 19, 20, 21]. We also replicated an 8 cubic metre block in the sea with concrete prepared according to Vitruvius’ specifications [18]. The concrete in the cores from the Roman harbours we sampled varies to some extent both in the composition of the mortar and the type of aggregate, but every structure tested made use of pulvis Puteolanus, now popularly called pozzolana, a type of
powdery, pumiceous, incoherent volcanic ash erupted from Campi Flegrei volcanoes around the Gulf of Pozzuoli at the northwest sector of the Bay of Naples [1, 12, 13, 14, 15]. The term “pozzolana” can be confusing, but it long ago became embedded in the archaeological literature; here it refers only to the volcanic ash from the Campi Flegrei. We have also found that this material was used in the mortar of a marine fish-tank on the coast of Portugal, outside the Straits of Gibraltar. The benefit of hydraulic pozzolanic mortar is that it can set and cure in the water, out of contact with atmospheric CO2, allowing concrete for harbour structures to be placed in inundated, or even completely submerged, forms. The pozzolana also enhances the long-term durability of the concrete [15].

This more than Mediterranean-wide trade in a bulk building material is not mentioned in surviving ancient literary or inscriptional sources, but clearly it was important to Roman harbour engineers for nearly 300 years. Harbours, of course, were the most important element in the physical infrastructure that made the Roman imperial economy, and thus the Roman imperial socio-political system, possible.

Various questions must be posed about the origins and spread of the technology for using hydraulic concrete made of hydrated lime and pozzolana, particularly in immense marine structures built far from Central Italy [21]. When was the formula discovered, and to what degree did engineers understand the mechanism of its function, and the capabilities of the material? How was the mortar prepared and mixed, and how was the concrete placed in the sea? Did Roman engineers make use of any other volcanic additives to contribute to the hydraulic qualities of their mortars, particularly around the city of Rome? How did the knowledge of the properties of pozzolana travel to large and small marine construction sites outside of Italy: through the movement of engineers, or by means of technical handbooks on harbour engineering? A careful consideration of the ancient Roman literary and inscriptional sources concerned with maritime concrete construction can help resolve some of these questions. Important Latin and Greek terms are provided within these translations in parentheses, and sections of the original Latin text follow the translation of particularly important or ambiguous phrases or passages.

2 The Testimony of Ancient Authors for Roman Maritime Concrete

We are fortunate that the handbook On Architecture (De architectura) by Vitruvius, completed around 20 BC, contains several explicit passages on pozzolana and its use in marine concrete, including discussion of the method of placement in formwork. Vitruvius is insistent that the pozzolana (pulvis, lit. “powdery earth”) intended for mortar used in submarine construction should be sourced from the Bay of Naples (De arch. 5.12.2), or—more specifically—the area around Baiae. “There is a kind of powdery earth (pulvis) that by its nature
produces wonderful results. It originates (nascitur) in the neighbourhood of Baiae and the territory of the municipalities around Mount Vesuvius. This material, when mixed with lime (calx) and rubble (caementum), not only furnishes strength to other buildings, but also, when piers (moles) are built in the sea, they set under water.” (De arch. 2.6.1)

Vitruvius goes on to speculate that the natural subterranean heat of this region is the cause of this useful capacity for setting underwater and the tuff (tofus) that occurs there, rising up from beneath the earth, is without natural moisture. “Therefore when three substances [lime, tuff, and pozzolana?] formed in a similar manner by the violence of fire, come into one mixture and take on the moisture all at once, they cohere. Hardened by the liquid they quickly form a solid mass, and neither waves nor the effect of water can dissolve them. It seems certain that the natural moisture (liquor) has been snatched from the tuff and pozzolana (‘ex tofo terraque) in the same manner as it is from limestone in lime-kilns (quemadmodum in fornicibus et a calce). Therefore, when unlike and unequal substances have been separated then united again into one substance, the hot thirst for moisture, suddenly quenched with water, boils with the heat hidden in the conjoined forms and causes them to unite furiously and quickly to take on the unified strength of a solid.” (De arch. 2.6.1-4).

Although the meaning is not entirely clear, Vitruvius seems to suggest that all three elements lack the liquid element (liquor) but have a latent heat (cf. De arch. 2.5.2-3). This heat is released by contact with water in an exothermic reaction [10]. There are echoes of this explanation in a passage of Dio Cassius’ History in which he describes the properties of the pozzolana used in the harbour Agrippa built in 37 BC near Baiae, a seaside resort renowned for its thermal waters.

“Now besides these products, the hill behind Baiae furnishes an earth (gē), the special nature of which I will describe. The subterranean heat cannot burn anything because its scourging properties are quenched by the admixture of ground water, but it can still separate and melt the substances with which it comes into contact. In consequence, the soft part of the earth is melted out by the heat, while the hard and as it were bony part is left behind. Hence the masses of earth necessarily become porous and when exposed to the dry air crumble into dust (könis). When this dust is mixed with water and lime (konía) they become a compact mass, and as long as they remain in the water they continue to set and harden. The reason for this is that the brittle element in them is disintegrated and broken up by the fire, which possesses the same nature, but by the admixture of moisture it is chilled, and so once again becomes completely dense and indissoluble.” (48.51.3-4)

In his Questions about Nature (Quaestiones Naturales), the first-century philosopher Seneca mentions pozzolana in the context of water that leaves a calcium carbonate deposit. “The water [of the Hebrus River] is adulterated and throws a sediment (limus) of such a nature that it cements and hardens objects. In just the same manner that the powdery earth of Puteoli (Puteolamus pulvis)
becomes rock if it touches water, so by contrast, if this water touches something solid it clings to it and forms concretions.” (QN 3.20.3)

There is a similar comment in Pliny’s Natural History: “But other creations belong to the Earth itself. For who could marvel enough that on the hills of Puteoli there exists a dust (pulvis)—so named because it is the most insignificant part of the Earth—that, as soon as it comes into contact with the waves of the sea and is submerged, becomes a single stone mass, impregnable to the waves and every day stronger, especially if mixed with stones quarried at Cumae.” (HN 35.166)

Seneca and Pliny both undoubtedly knew that pozzolana had to be mixed with lime to make a proper mortar, so they may just be glossing over the full formula to make a rhetorical point. On the other hand, these observant natural scientists may simply be referring to natural concretes or volcanic tuffs that form through lithification of volcanic ash during alteration by ground and surface waters, or even to the secondary mineral cements formed by the alteration of coastal deposits of volcanic ash in seawater [12]. It is possible that builders or engineers in the late third century BC noticed this phenomenon and experimented with the substitution of pozzolana for beach or river sands in their mortars.

Early experimentation with pozzolanic mortar for maritime construction probably took place at Puteoli, which in the third and second centuries BC was the only important port in the vicinity of the pozzolana deposits of the Campi Flegrei volcano. Until completion of the Claudian and Trajanic harbours at Portus, Puteoli served as the major harbour for the city of Rome, 200 km away, particularly for grain imports [16]. At some point early in the second century BC, a long breakwater composed of large, closely spaced concrete piers (pilae) connected by low concrete vaults was constructed to accommodate the growing sea trade serving Rome. In the early first century AD Strabo praises the natural suitability of the local “sand-ash” at Puteoli for the construction of concrete breakwaters. “Puteoli has become a very great emporium, since it has an artificially constructed harbour, something made possible by the natural qualities of the local sand (ámmos), which is well suited to the lime and takes a firm set and solidity. Therefore, by mixing the sand-ash (ammokonía, i.e. pozzolana) with the lime, they can run mole out into the sea and in this way make the exposed shore into a protected bay, so that the biggest cargo ships can anchor there safely.” (Geography 5.4.6)

Although there are ancient and modern representations of the harbour works at Puteoli, the ancient remains unfortunately now are inaccessible beneath a modern breakwater.

There are numerous concrete harbour installations around the northern shores of the Bay of Naples, many of them associated with the massive installations of the Praetorian Fleet at Misenum. A tomb monument found in the region was dedicated to a Lucius Iulius Valens who was a caementarius (“worker in concrete”) with the Classis Praetoria Misensium (CIL 10.1.3414). Since he was a duplicarius, a soldier receiving double salary because of a special skill, Lucius might have been some sort of engineer of maritime concrete construction.
Pliny mentions the importation of *Puteolanus pulvis* to Portus to make concrete for one of the breakwaters of the emperor Claudius’ new harbour basin. He describes a gigantic ship built for the emperor Caligula to carry an Egyptian obelisk to Rome that was sunk on site and used as a kind of caisson. “It is certain that nothing more amazing than this ship has ever been seen on the sea… Its length took up a large part of the left side of the port facilities of Ostia, for under the emperor Claudius it was sunk there. Three great masses as high as towers were built on it for this purpose with the dusty earth of Puteoli (*Puteolano pulvere*), and brought here.” (*Nat.* 16.202)

The impossible suggestion that the concrete towers were built on the ship before it arrived at Portus may result from textual corruption, or from confusion with the procedures involved in using a floating ship as a caisson. Suetonius, in his *Life of Claudius* (20.3), states that the ship was scuttled, and then piers were built on top.

Vitruvius provides us with our only detailed description of how Roman builders constructed concrete structures in the sea with pozzolanic mortar [2, 3, 14, 18, 19]. “If, however, we have no natural harbour situation suitable for protecting ships from storms, we must proceed as follows. If there is an anchorage on one side and no river mouth interferes, then a mole composed of concrete structures (*structurae*) or rubble mounds (*aggeres*) is to be built on the other side and the harbour enclosure constructed in this manner. Those concrete structures that are to be in the water must be made in the following fashion. Volcanic ash (*pulvis*) is to be brought from that region which runs from Cumae to the promontory of Minerva (the Bay of Naples), and this is to be mixed so that in the trough the proportions are two parts ash to one of lime. Next, in the designated spot, formwork (*arcae*) enclosed by stout posts and tie beams (*stipitibus robusteis et catenis inclusae*) must be let down into the water and fixed firmly in position. Then the area within it at the bottom, below the water, must be levelled and cleared out, (working) from a platform of small crossbeams (*ex transtris*?). There, the aggregate, and the mortar from the trough mixed as described above, must be heaped up (*caementis ex mortario materia mixta…ibi congerendum*), until the space left for the concrete within the form has been filled…” (*De arch.* 5.12)

In addition to *pozzolana* from Puteoli, there are volcanic sand deposits in the region of Rome that are effective pozzolanic mortar aggregates. The Romans made good use of them for terrestrial structures [1, 9, 10, 11, 12]. Vitruvius, however, is careful to distinguish the origin and character of these red, black, and light grey sands, which he called *harenae fossiciae* (“quarry sands”) from the fine-grained grey *pulvis* that came from Puteoli (*De arch.* 2.4, 2.6.4-6). He recommends the *harenae fossiciae* for structures on land: “When the lime (*calx*) has been slaked, then the mortar is to be mixed in such a manner that—if pit sand (*harena fossicia*) is used—three parts sand and one part lime are poured in.” (*De arch.* 2.5.1) For marine structures, the Vitruvian ratio was two measures of *pulvis* *Puteolanus* to one of lime (*De arch.* 5.12.2). For structures on land, Pliny (*HN* 36.175) specifies a pozzolanic mortar with a ratio of four measures of *harena*
fossicia to one of lime. Vitruvius is careful to note that, while there are quarries for harena fossicia in the volcanic landscape of Etruria, north of Rome, deposits of pulvis do not occur there. “Since there are also numerous hot springs in Etruria, the question remains why one does not find there also the volcanic powder (pulvis) through which in the same manner concrete sets underwater (sub aqua structura).” (De arch. 2.6.4-5)

Vitruvius sums up his discussion of harenæ fossicæ and pulvis Puteolanus with the comment that “Some materials have advantages for structures on land (terrenis aedificiis), others for moles built in the sea (maritimis molibus).” (De arch. 2.6.6) The distinctive application of the two volcanic products is reflected in the cores taken by the ROMACONS project, even at sites such as Portus, where imported pozzolana was used for the structures below water and local harena fossicia for structures above.

The importance of lime in ancient concrete work cannot be underestimated. The lime paste, however, drives the chemical reaction that produces the hydraulic properties in the mortar [12], and the Romans recognized an array of limes with varying properties. Lime paste, in fact, was and remains the most expensive ingredient in a concrete mix [5, 13], and Pliny (HN 36.176) states that skimping on lime in a mortar mix was the main reason for the collapse of buildings in Rome. This type of fraud remains a serious problem in developing countries. Vitruvius emphasizes the need for selectivity (De arch. 2.5.1; cf. Pliny HN 36.174): “…one must be careful that, in regard to lime (calx), it is burned from white rock, whether (hard) stone or (softer) silex. The lime from close-grained, harder stone will be the most useful in structural forms, while that made from porous stone will be best in plaster.” Vitruvius explicitly states that the lime should be slaked before it is added to the mortar mix (De arch. 2.5.1). Pliny (HN 36.176) refers to “old building laws” requiring the ageing of intrita—which in the context should be slaked lime putty—for three years prior to use.

3 How did expertise with this technology spread?

Clearly, Roman engineers had a very nuanced understanding and strong opinions based on empirical experience regarding the geologic materials that went into both terrestrial and submarine mortars. The ROMACONS Project has revealed that the practice of obtaining pulvis Puteolanus from the Campi Flegrei area was applied throughout the Mediterranean, despite the presence of suitable pozzolans outside Italy, at Santorini or Melos, for example. Indeed, French engineers used “Santorini earth” for marine structures associated with the Corinth and Suez canals [6]. Roman engineers also had a sophisticated knowledge of both stationary and floating forms for placing pozzolanic concrete in the marine environment, and of stationary cofferdams that could be pumped dry to allow the placement of non-hydraulic concretes below water level [2, 3, 19].
How did this information about the proper materials and techniques for marine construction travel around the entire Mediterranean world, from Alexandria and Caesarea Maritima on the east to Portugal on the west? For example, the core of the two enormous breakwaters sheltering the outer basin at Caesarea was composed of approximately 35,000 cubic metres of hydraulic concrete. The mortar was made with \textit{pulvis Puteolanus} shipped 2,000 km from the Puteoli region, approximately 24,000 cubic metres weighing 52,000 tons [8]. It seems likely that Herod requested technical assistance from Rome for his enormous project, probably from his friend Agrippa, who had built the harbour of Portus Iulius near Puteoli. Agrippa would have sent harbour engineers out from Italy, military engineers, like the \textit{caementarius} Valens mentioned above who was stationed with the fleet at Misenum. These engineers, reflecting the same practical expertise as their contemporary Vitruvius — himself a retired military engineer — evidently recommended the use of \textit{pulvis Puteolanus}, augmented with local sand, coarse aggregate, and lime [20]. Elaborate single-use barge forms identical to those documented at Caesarea were used in the construction of concrete structures in the harbour of Alexandria in the first century AD [2, 3, 7]. While the movement of military engineers around the Mediterranean is the most likely explanation for the spread of this type of harbour construction technology, it is also possible that sub-literary technical manuals incorporating the technical information in written and graphic form moved with these engineers, or even independently. The traces of manuals of this type (\textit{commentarii}) have been discerned in the archaeological evidence for military and agricultural equipment, and wooden pumps, and there is no reason they could not have existed for the elements of concrete construction in the sea as well [17]. The existence of such manuals would help explain the use of \textit{pulvis Puteolanus} in the maritime concrete of small, out of the way Roman harbours such as that at Chersonisos on Crete, where imperial involvement is unlikely [4, 21].

4 References