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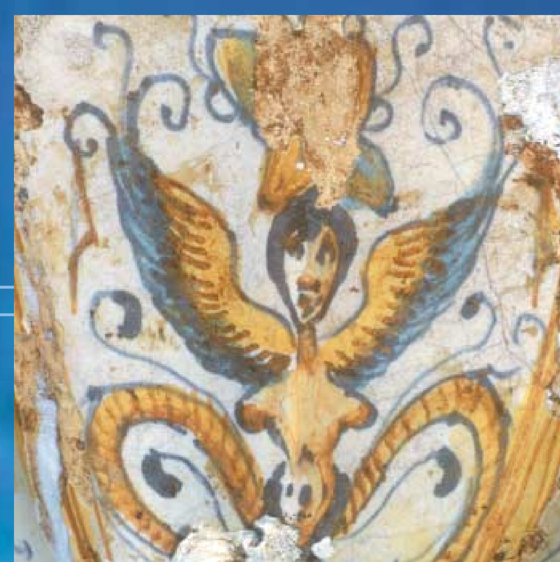

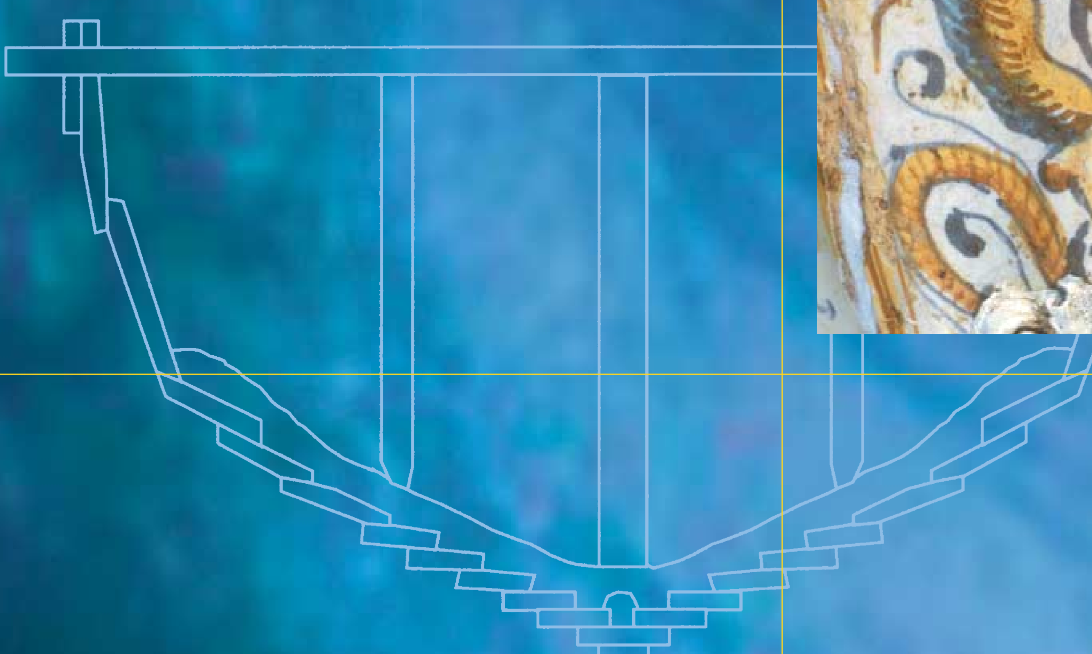

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The ROMACONS Project: a Contribution to the Historical and Engineering Analysis of Hydraulic Concrete in Roman Maritime Structures

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Since all long-distance trade in the Roman world travelled by water, Roman harbour design and construction have special importance. Harbour excavation must be supplemented by analysis of the components of the hydraulic concrete, structural analysis of the cementing materials, and consideration of the design of the wooden formwork. The authors have begun collecting large cores from concrete blocks at Roman harbours and other maritime structures, analysing the materials used, the method of placement, and the structural characteristics of the resulting concrete. These data have provided new information on the engineering properties of Roman concrete, the process of funding and execution, and the trade in the volcanic ash which was the crucial component of hydraulic concrete.

Key words: Roman hydraulic concrete, formwork, harbour, pozzolana, Vitruvius.

Some time in the Republican period, perhaps in the 3rd but certainly by the 2nd century BC, Roman builders discovered how to create hydraulic mortar, a building material with enormous potential (Blake, 1947: 308–18; Blackman, 1982: 196–7; Lechtman and Hobbs, 1987; Oleson, 1988; Lamprecht, 1996; Gazda, 2001). Standard mortars and plasters of varying quality, composed of hydrated lime, beach or river sand, and water had been used in the circum-Mediterranean world since the 6th or 7th millennium BC (Gourdin and Kingery, 1975; Kingery *et al.*, 1988). Hydraulic mortar differs in that a pozzolanic additive either supplements or is substituted for the relatively pure silica sand. For the Romans, this pozzolanic additive was a sand-like volcanic ash, *pulvis puteolanus* ('earthy material from Puteoli'), surviving in Italian as *pozzolana*, a term now anglicised and applied to a variety of materials—such as sintered ash—that have the same effect on modern cement (Quietmeyer, 1912: 7–45). Pozzolanic materials, particularly volcanic ash, are composed of chemically reactive aluminosilicates which, when mixed with lime and water, produce a series of hydrated calcium aluminates and silicates (Cowper, 1927; Lechtman and Hobbs, 1987: 89). Although the chemistry is even now not completely understood,

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these compounds cause the hydraulic mortar to set slowly, particularly under water, and become extremely hard. This mortar binds together added stone aggregate (*caementa* in Latin), which both adds compressive strength to the mix and reduces the amount of mortar needed. The Romans termed the resulting material *opus caementicium* or just *caementicium*, concrete (e.g. *CIL* 1.1793.6, 3.633; Vitruvius, *On Architecture* 6.8.9; Blake, 1947: 324–52; Lugli, 1957: 363–442). As Vitruvius makes clear, not all Roman mortars were hydraulic in character, but there was no special single term to designate the difference. This paper concerns only hydraulic concrete used in maritime structures.

The potential of this remarkable material was quickly realized, as Roman engineers began to substitute monolithic concrete forms for arched and vaulted structures built of laboriously-carved and precisely-fitted stone blocks. The resulting profound changes in Roman architectural design have been termed a 'revolution' (McDonald, 1965; Lechtman and Hobbs, 1987), and their effects can still be felt today. Roman engineers quickly realized the special suitability of this material for the construction of hydraulic installations, bridge footings, and harbour structures. The mastery of hydraulic concrete, combined with other engineering innovations, enabled Roman engineers to construct harbours anywhere political, economic or military considerations dictated and not simply where advantageous physical features existed. Since virtually all heavy cargoes or long-distance trade in antiquity travelled by sea, this new capacity made a crucial contribution to the economic activity of the Mediterranean world, and fostered the spread of Roman rule.

It is not certain where this great technological advance first occurred, since the earliest maritime structures built of hydraulic concrete have probably disappeared, but the region around the port city of Puteoli (modern Pozzuoli) at the north end of the Bay of Naples is the most likely area (Lechtman and Hobbs, 1987: 89). In his handbook *On Architecture*, completed *c.*25 BC, the architect Vitruvius specified that pozzolana (*pulvis*, or *harena fossicia*, lit. 'quarry sand') from the area around Baiae, a seaside resort next to Puteoli (2.6.1) or, more generally, from the entire coastline of the Bay of Naples (5.12.2–3), had to be used to produce hydraulic concrete. At about the same time, Strabo (*Geography* 5.4.6) reported that Puteoli:

> has become a great trade centre, since it has man-made harbours—thanks to the natural quality of the sand. Measured out in proper proportion to the lime, the sand forms a strong bond and cures solidly. In consequence, by mixing the sand-ash [*ammokonia*] with the lime, they can run break-waters out into the sea and turn open beaches into protected bays, so that the largest merchant ships can moor there safely.[1]

Approximately a century later, Pliny the Elder specified that pozzolana should be taken from the hills around Puteoli (*Natural History* 35.166), and both he (*Natural History* 16.202) and his contemporary Seneca (*Questions about Nature* 3.20.3) refer to pozzolana as *pulvis puteolanus*. The focus of these ancient sources on the northern end of the Bay of Naples, along with the importance of the harbour at Puteoli after 168 BC (Polybius, *History*, 3.91.3–4) and of the whole Bay of Puteoli as a centre for maritime villas in the 2nd and 1st centuries BC (Dubois, 1907; Frederiksen, 1959: 2039–43; D'Arms, 1970: 7–8, 17–38), strongly suggest that the formula for hydraulic mortar originated in this region, and that it remained an important source of pozzolana well into the empire. According to Vitruvius (2.6.1):

> There is a kind of powdery sand [*pulvis*, i.e. pozzolana] which by its nature produces wonderful results. It is found in the neighbourhood of Baiae and in the lands 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 are built in the sea, they set under water ... and neither the waves nor the force of water can dissolve them.

The mortar should be mixed 'in the proportions of two parts pozzolana to one of lime'. He also provides our only detailed description of the wooden formwork into which Roman concrete was poured (Schläger, 1971; Oleson, 1985; Oleson, 1988; Brandon, 1996; Brandon, 1999) (Fig. 1).

> Powdery sand [*pulvis*, i.e. pozzolana] is to be brought from that region which runs from Cumae to the promontory of Minerva and mixed in the mortar used in these structures. Next, in the designated spot, formwork enclosed by stout posts and tie beams is to be let down into the water and fixed firmly in position. Then the area within it at the bottom, below the water, is to be levelled and cleared out, [working] from a platform of small crossbeams. The building is to be carried on there

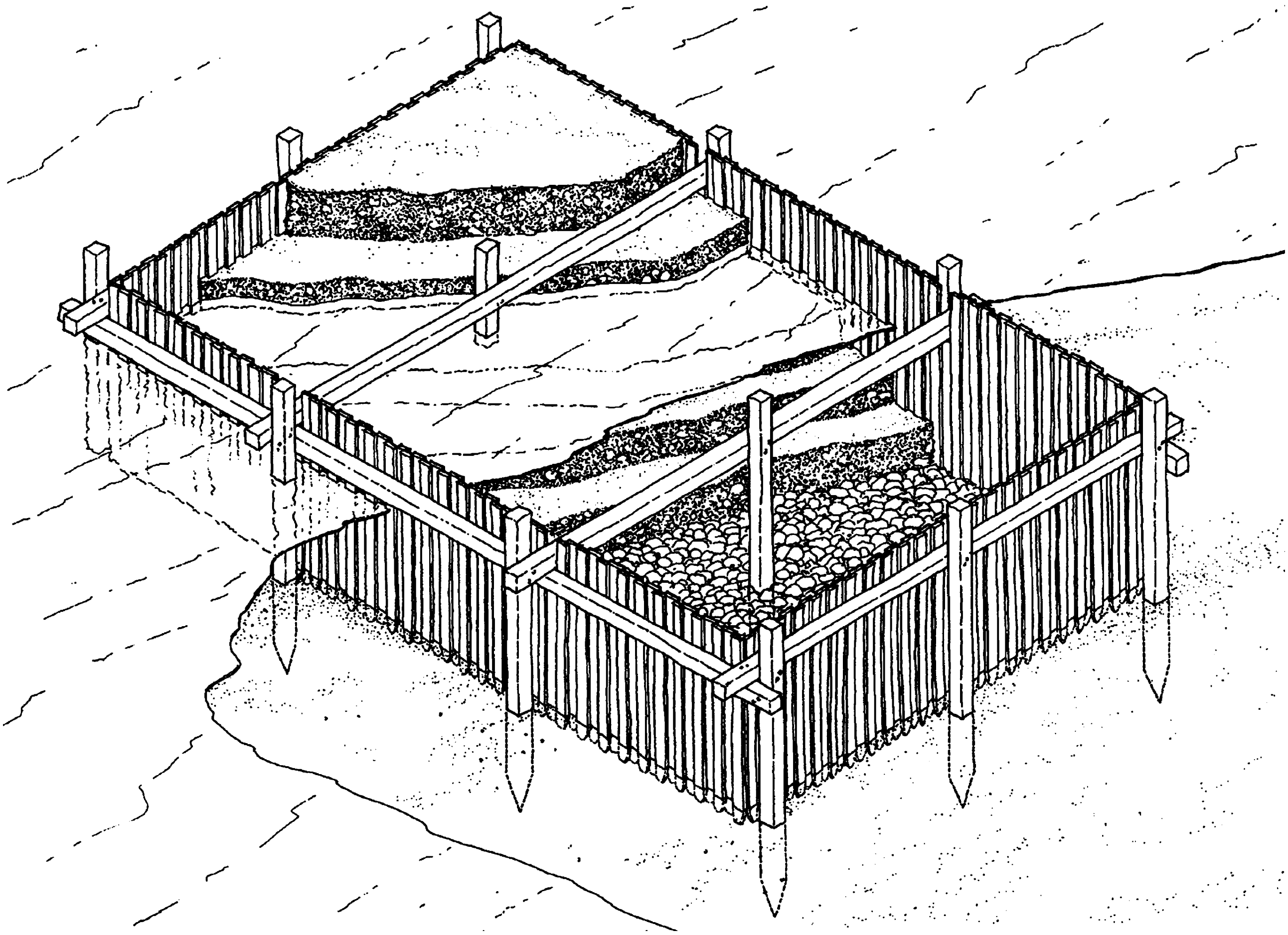

Figure 1. Vitruvius' formwork for hydraulic concrete. Reconstruction. (C. Brandon)

with a mixture of aggregate and mortar, as described above, until the space left for the structure within the form has been filled ... But in locations where the powdery material does not occur naturally ... Let double-walled formwork [*arcae duplices*, i.e. cofferdams] be set up ... held together by close set planks and tie beams, and between the anchoring supports have clay packed down in baskets made of swamp reeds. When it has been well tamped down in this manner, and is as compact as possible, then have the area bounded by the cofferdam emptied and dried out by means of water-screw installations and water-wheels with compartmented rims and bodies. The foundations are to be dug there, within the cofferdam ... and then filled in with a concrete of aggregate, lime, and beach sand (Vitruvius, 5.12.2–3, 5–6).

As Vitruvius makes clear, only the use of hydraulic mortar allows the concrete to be placed in forms filled with sea water. A century later, Pliny the Elder describes the same process (*Natural History* 35.166):

on the hills of Puteoli exists a powdery sand [*pulvis*] 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.

Roman architects were particular about the quality of their lime as well:

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 most useful in structural forms, while that made from porous stone will be best in plaster. Once it has been slaked, then let the mortar be mixed three parts quarried sand [*harena fossicia*, i.e. pozzolana] to one of lime; or if river or marine sand is thrown in, two parts sand to one of lime ... . Furthermore, if anyone adds a third part of crushed and sifted burnt brick into the river or marine sand, he will make the composition of the material better to use (Vitruvius, 2.5.1).

He specifies a leaner lime/pozzolana mixture here (1:3) compared with the 1:2 mix quoted

Figure 2. Map of coring sites in Italy.

earlier. The context suggests that the mortar richer in lime was a response to the use of the mortar in inundated forms. The crushed ceramics represent an artificial pozzolanic additive used to supplement non-pozzolanic sand, producing a mortar particularly suitable for waterproofing cisterns.

Formations of natural concrete at sea level around Puteoli, formed by the percolation of ground water saturated with calcium carbonate through strata of pozzolana, may have suggested to Roman builders the formula for hydraulic mortar. Seneca may be referring to this natural concrete when he writes 'Just as pozzolana [*pulvis puteolanus*] becomes rock if it touches water ... ' (*Questions about Nature* 3.20.3). Alternatively, as conventional mortared rubble construction became more common in the 3rd century BC, builders may simply have found that the substitution of local volcanic ash for sea sand resulted in a stronger mortar and one that could set under water. Hydraulic concrete can be documented in use for structures on land in Central Italy by the later 3rd century BC (Adam, 1994: 79, 127–8), but either the earliest structures built in the sea have been lost (which should not be surprising), or the invention was only applied to maritime structures a century later. Gianfrotta, who has studied many maritime concrete structures along this coastline, has not identified any installations that appear to date before the late 1st century BC (1996: 72; 1999).

At present, the earliest surviving example of a major structure built with hydraulic concrete is in the harbour at Cosa, a Roman colony on the coast of Etruria, 150 km north of Rome (McCann *et al*., 1987) (Fig. 2). The pioneering excavations conducted at Cosa in the 1960s and 1970s by A. M. McCann and an interdisciplinary team uncovered five hydraulic concrete *pilae* (large, free-standing blocks) constructed on or adjacent to an earlier rubble breakwater (Gazda and McCann, 1987: 139–40) (Figs 3–4). The date of their construction, either late 2nd century or mid 1st century BC, is still the subject of debate (cf. Gazda and McCann, 1987: 155, but see n.84; Gazda, 2001: 163; Gazda, forthcoming). A C14 sample from Core PCO.2003.01 from the Cosa Port (see Appendix) provided a date of 2020 ± 40 B.P., giving a range of 57 BC to AD 33. Even if the project belongs to the mid 1st century BC, Cosa remains the earliest known harbour using Roman hydraulic concrete. The pozzolana for the mortar was imported from the Puteoli region, but the tuff aggregate seems to have originated at quarries around Bolsena, 60–80 km to the north-east (Gazda, 1987: 76 n.5; Gazda and McCann, 1987: 145–6). Nevertheless, since Cosa was not a major state engineering project and is far from the region where this type of mortar seems to have been developed, it is likely that the innovation was applied earlier, even if tentatively and experimentally, at other Italian sites. The Bay of Naples would be the obvious location, in particular Puteoli itself, which served as one of the main harbours for the city of Rome until the completion of the Claudian harbour at Portus in the 50s AD.

By the end of the 1st century BC the use of hydraulic concrete had become virtually routine for the construction of harbours and other maritime structures in Italy and in some other regions of the Mediterranean (Blackman, 1996; Brandon, 1996). Numerous breakwaters, isolated *pilae*, and seaside tanks for raising fish (*piscinae*) were built along the coast of Etruria and the Bay of Naples in the last decades of the 1st century BC, testing and extending the remarkable capabilities of hydraulic concrete (Gianfrotta, 1996: 65–76). The explosion of interest in this new technology, first in Italy and then throughout the empire, did not immediately invalidate the older, more traditional methods of building harbours (Hohlfelder, 1985: 85; Oleson, 1988: 155; Hohlfelder, 1996: 91–2). Wooden quays and rubble breakwaters, with or without buildings surmounting them, continued to be constructed when they were more practical. The new technology simply expanded the repertoire of construction options for harbour builders (Oleson, 1988: 148). Not every city or town needed hydraulic concrete when simpler solutions were

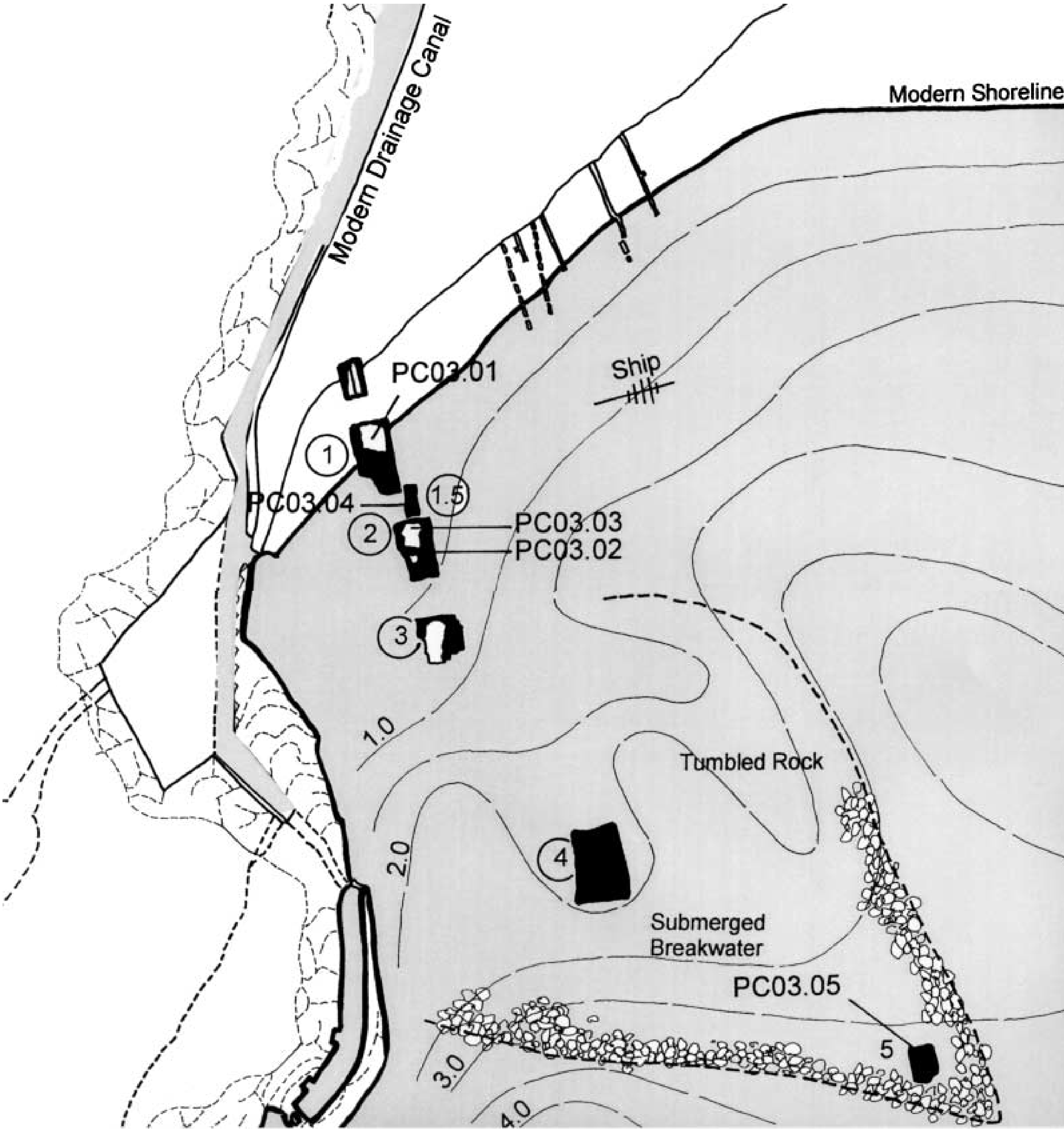

Figure 3. Cosa: Plan of outer harbour with coring locations (after McCann *et al.*, 1987).

available, for example the small town of Aperlae in Lycia (Hohlfelder and Vann, 2000: 133).

Modern research on Roman hydraulic concrete

Although the use of hydraulic concrete in harbour engineering represented a major step forward for ancient technology, the construction material itself has not received the scholarly attention it deserves (Gazda, 2001: 153). Most studies of Roman concrete have focused on terrestrial rather than maritime structures and have tended either to address site-specific questions or to offer general historical surveys of architectural development.

Figure 4. Cosa: Pier 2, side view from west.

Engineers and materials scientists have published a few detailed studies of the chemical and mechanical properties of Roman plaster, mortar, and concrete over the last few decades, but often without the collaboration of archaeologists (Lamprecht, 1996: 54–87; list in Gazda, 2001: 155–61). Unfortunately, the goals and laboratory methods of these studies have varied dramatically, and the collection of samples from monuments within and outside Italy has tended to be opportunistic rather than systematic. As a result, it is difficult to reconcile the disparate laboratory results. Studies focused specifically on Roman hydraulic concrete have been even more limited in number and scope (e.g. Roy and Langton, 1980; Branton and Oleson, 1992a and b; Tsatskin 1999). In response to these circumstances, Oleson, Brandon and Hohlfelder founded the Roman Maritime Concrete Study (ROMACONS) in 2001, a comprehensive research program focused on the collection and analysis of large cores of hydraulic concrete from carefully-selected, well-dated structures (Oleson *et al.*, forthcoming). The team has begun development of a detailed and extensive database of hydraulic concrete, based on consistent and comprehensive protocols of chemical and mechanical testing of cores recovered in a standard and repeatable fashion from a variety of maritime concrete structures in Italy. We plan to extend the study to sites elsewhere in the Mediterranean in 2005.

ROMACONS research questions

The ROMACONS team of specialists from both humanities and sciences has begun to address many of the unanswered questions concerning the history of Roman hydraulic concrete, the technology of its production and use in maritime structures, and its structural characteristics. Our pioneering application to ancient concrete structures of a sampling technique that allows the collection of large cores from the interior of the concrete mass has opened up new opportunities for testing and analysis.

How closely does the Vitruvian formula for hydraulic concrete and the formwork designs he describes correspond to engineering practice in Italy and the rest of the Mediterranean world during the Republic and Empire? Obviously Vitruvius did not invent hydraulic mortar or pioneer its application, nor did he present a comprehensive handbook of contemporary procedures. Nevertheless, it is important to determine to what degree his information was based on contemporary practice, and when, where and why builders deviated from the Vitruvian model. Evidence uncovered during the underwater excavation at Caesarea Palestinae indicates that the engineers of Herod's harbour, probably Italians familiar with contemporary practices in the Bay of Naples, went to enormous trouble to import pozzolana from that same region (Branton and

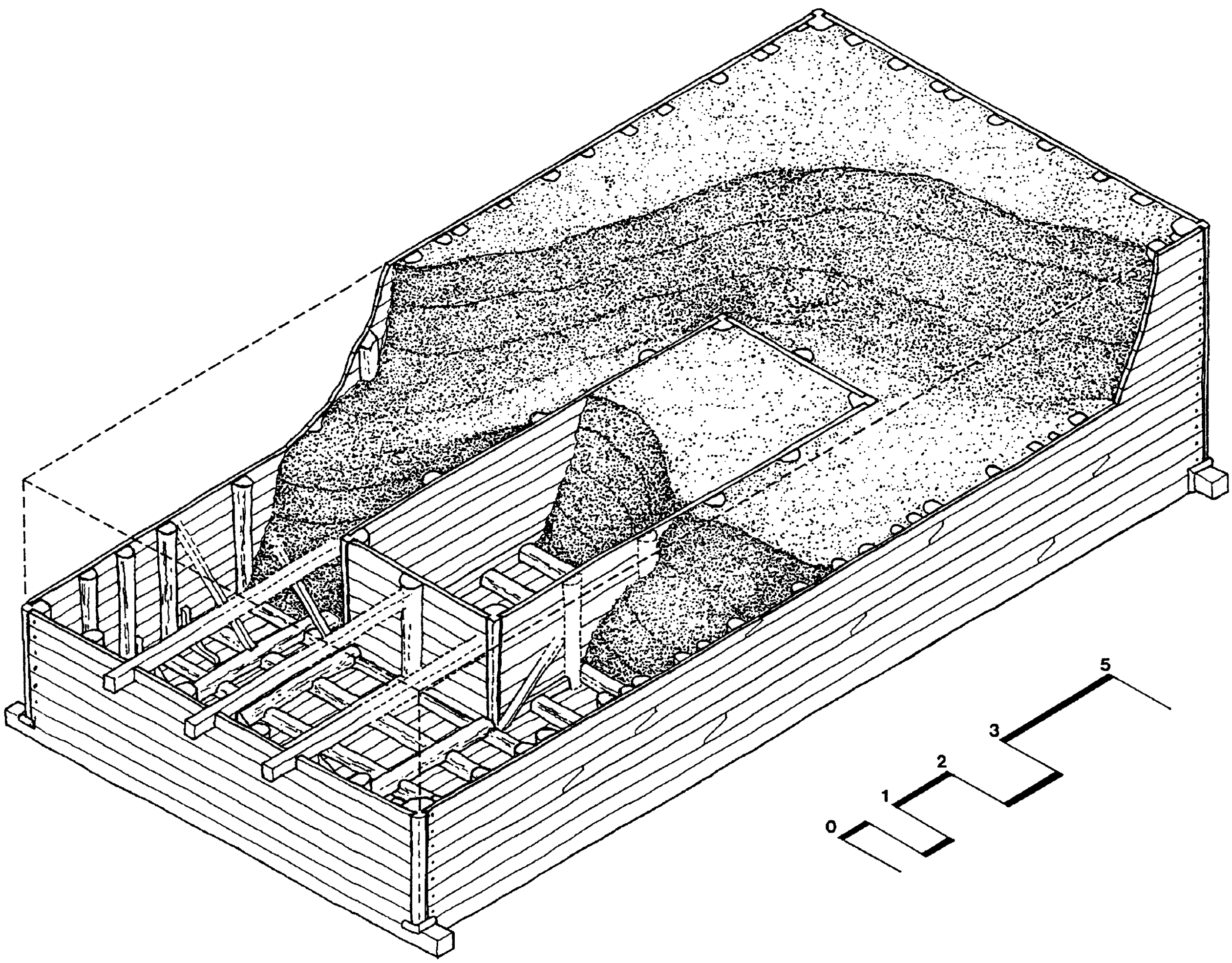

Figure 5. Caesarea: single-use barge formwork. Reconstruction. (C. Brandon)

Oleson, 1992a and b). Nevertheless, they employed formwork very different from that described by Vitruvius, along with a mix of hydraulic and non-hydraulic mortars in a single structural unit. The single-use barge forms may have been conceived in Hellenistic Alexandria (Brandon, 1997; Goddio *et al.*, 1998; Brandon, 1999; Hohlfelder, 2000: 249–50; Brandon, 2001) (Fig. 5). There are also so far no known examples which follow Vitruvius' laborious method for constructing a concrete breakwater out into the open sea by allowing blocks poured and cured on a platform to be undermined and fall into position (5.12.3–5; Oleson, 1988: 150; Brandon, 1996: 27). At the harbour of Kenchreai, which was still under construction when *On Architecture* appeared, the building programme bears little resemblance to the procedures specified by Vitruvius (Hohlfelder, 1985: 84–5).

It is likely that the natural challenges posed by a particular harbour site required some creative expansion and modification of existing technology to facilitate construction, and that the building program at King Herod's harbour, which departed in dramatic fashion from the Vitruvian model, was not an isolated case. If Vitruvius' text was not a general guide, did some other written handbook of harbour design and construction ever appear and affect projects across the empire? Were the engineers skilled in the use of this material for marine structure few in number and always associated in some way with the imperial court, or did knowledge of the materials and procedures spread widely by some other method of transmission? Hohlfelder (1996: 95) has suggested that the builders who assisted in repairing the strategic harbour facility at Paphos may have been the same individuals who had worked at Caesarea Palestinae, dispatched to both projects by Augustus or Agrippa. Alternatively, were there also sub-literary harbour engineering manuals that circulated widely and independently of the military and the royal house (Oleson, forthcoming)?

The formwork or shuttering into which the hydraulic concrete was placed to set warrants detailed study, both the surviving wooden structures and the casts they have left in the concrete. At Caesarea, Antium, Cosa, Laurons, Carthage and many other sites around the Roman Empire significant remains of formwork have been found that document a remarkable variety in design (Felici, 1993; Blackman, 1996; Brandon, 1997; Felici and Baldieri 1997; Blackman, 1998; Felici, 2002). The use of mortise and tenon joints in formwork at Caesarea, Carthage, and Chalon-sur-Saône provide a tantalising glimpse of a cross-over of technology between civil engineering and ship construction and hint at the complexity of the situation (Hurst, 1977: 189; Brandon, 2001). Will any norms appear as our database of formwork design expands? Even this one aspect of harbour technology, when better known, will move us closer to understanding whether a standard construction protocol ever evolved for using hydraulic concrete in building or repairing maritime installations.

Another major research question involves the use of pozzolana and tuff from the Bay of Naples in construction projects outside Italy, and the logistics of its transport over long distances. Analyses carried out by Oleson and Branton on samples of mortar from the harbour at Caesarea Palestinae indicated that the source of the pozzolana and the tuff aggregate was the Bay of Naples 2000 km to the west (Branton and Oleson, 1992a and b). This startling conclusion raised many questions regarding the trade in these bulky construction materials. A recent analysis of the chemical composition of pozzolana from a harbour structure at Chersonesos in Crete also indicates the Bay of Naples as its source (Brandon *et al.*, forthcoming). How many other harbours will provide a similar result and prove the existence of a Mediterranean-wide trade in this banal but vital material? Did Roman harbour engineers ever discover that sources of pozzolana outside Central Italy, for example at Santorini or Melos, functioned just as well?

The transport of many thousands of tons of Italian pozzolana for use in the construction of the harbour of Caesarea Palestinae may be explained in part by the opportunistic use of Roman grain freighters (Gianfrotta, 1996, 75; Hohlfelder, 2000: 251). After unloading a cargo of wheat at Ostia or Puteoli, these ships could have taken on a cargo of pozzolana at Puteoli, then set a course for Caesarea Palestinae—or any other major harbour project within striking distance of a source of bulk food exports. After unloading the pozzolana and taking on local ballast, they could have continued on to Alexandria. A guild of *saburrarii* is documented at Portus (*CIL* XIV.102), labourers who dredged gravel or sand from the harbour basin to be used as ballast. At Puteoli individuals such as these could have been detailed to load cargoes of pozzolana instead of commercially useless ballast.

While this explanation works well for major state harbour projects as at Caesarea, it is more difficult to explain how pozzolana was brought to the minor harbour of Chersonesos. How large were the transport ships, and who conducted the trade? Several Roman ships which sank off the coast of France were carrying partial cargoes of pozzolana, presumably to be used for construction (Parker, 1992: 250; Joncheray and Joncheray, 2002: 85). Since most merchant ships in the Roman Mediterranean were engaged in *cabotage* rather than single cargo bulk trade from producer to consumer (McCann and Oleson, forthcoming), was it this kind of ship that brought pozzolana from the Bay of Naples to Chersonesos? If so, how far from the source was this trade profitable?

The study of hydraulic concrete technology also must address the issues surrounding the labour force that used this material to build Roman harbours. Were there separate specialist *collegia*, unknown from epigraphical evidence? Were seasonal labourers, such as the *saccarii* (grain handlers), *urinatores* (salvage divers), or *saburrarii* (providers of ballast) at Ostia, used for work on the construction of Portus during Claudius's reign (Oleson, 1976; Thornton and Thornton, 1989: 89)? The *saburrarii* and *urinatores*, in particular, would already have been skilled in moving construction materials in and under the water. Was slave labour used in conjunction with free workers, and how were the workers organised and sustained during construction? How were the costs of harbour construction projects borne? Was imperial largesse ever augmented by local euergetism, and if so, under what circumstances?

Regarding the hydraulic concrete itself, we must determine whether the formulas for mixing the material varied according to location or chronology, and if so, why. One sample of mortar from the Baths of Caracalla revealed a 2:1 ratio of pozzolana to lime (DeLaine, 1997: 123), but Vitruvius specifies a 2:1 ratio for submerged structures, a

3:1 ratio for land structures (see above). What will it mean if the ROMACONS analyses show constantly varying mixes? Will a large enough database, highlighted by some dated samples, permit the dating of maritime structures on the basis of ingredient analysis and percentages alone?

We also intend to examine the relative compressive strengths and porosity of concrete samples from different sites and chronological eras. Will this study reveal consistency or variability? The use of aggregates must also be examined more closely. Did the function of a maritime structure determine the type of aggregate, as it did for terrestrial structures (Adam, 1994: 183–85; DeLaine, 1997: 85), or the relationship to sea level? How did the Romans compact their concrete during construction under water to ensure that it filled completely the forms into which it had been placed to set? How did they prevent separation of the lime and pozzolana, or of the mortar and the aggregate during placement and setting?

Sampling Roman maritime concrete structures

Roman concrete is not a homogeneous material. Unlike modern mortars and concrete in which the lime and cement have the consistency of a powder and are uniformly combined, Roman hydraulic concrete included poorly-mixed particles of lime and pozzolana which varied considerably in size, despite attempts at sifting (DeLaine, 1997: 110, 140) (Fig. 6). In addition, the aggregate varied in size and composition and was unevenly distributed within the concrete. Consequently, it is necessary to take a number of samples in order to obtain reasonably representative results from a particular structure. Since these ancient structures are inevitably important and highly visible cultural heritage monuments and their conservation and protection is a concern, sampling strategy is an important and sometimes controversial issue (Oleson *et al.*, forthcoming; cf. Raban, 1992). The standard method used by the construction and civil engineering industry for sampling modern concrete structures for testing and evaluation involves the use of a diamond core-drilling rig to take cores approximately 10 cm in diameter. The cores have predictable characteristics and can be subjected to a recognized standard set of tests.

This method is ideally suited for modern concrete, with a uniform consistency and relatively small aggregate. In the case of Roman concrete, which uses much larger aggregate, compressive

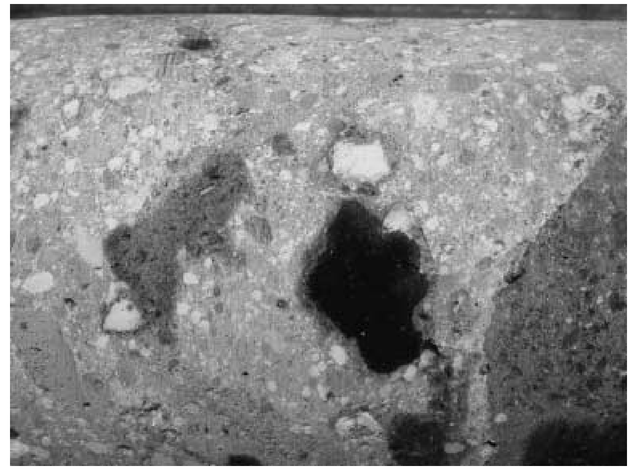

Figure 6. Core POR.2002.02, detail at −1.75 m.

testing cannot be carried out unless sections of mortar are recovered that have an aspect ratio of diameter to height of 1:2. Samples need to be carefully selected to ensure that the large aggregate does not induce shear failure along sloping surfaces within the matrix. As a result, longer cores have to be extracted than for modern concrete. At the same time, it is also often difficult to extract an intact core from Roman concrete structures, since—as the ROMACONS fieldwork has shown—even large *pilae* that appear to be uniform masses consist of layers of mortar varying in consistency and aggregates varying in hardness. During the coring process, the cores tend to fracture along the lines of least resistance, and the harder materials can grind up the softer.

The upper surfaces of the remains of Roman maritime structures are now often at sea level or just below. Since this is a high-energy zone, working conditions can be very difficult in even a slight sea swell. Weather conditions therefore significantly limit the times that coring can take place. The erection and fastening of the drilling rig even on the exposed upper surface of a marine structure can also be difficult, since the effects of erosion and marine encrustation make the surface uneven and soft. Despite all these problems the cores, once obtained, provide a completely new vision of Roman hydraulic concrete structures. The previous methods of sampling involved either smashing fragments off the outside of a structure with a heavy hammer and chisel, or salvaging interior samples from a structure being demolished to make way for a modern construction project. Neither procedure was well controlled or provided a complete sample, the mechanical characteristics of the samples were considerably altered in the process of collection, and the Roman structure suffered damage. Surface-collected samples, in particular, cannot be representative of the whole block, and their collection requires the removal of a significant amount of the protective marine growth, involving the risk of long-term damage to the structure. Core sampling, on the other hand, despite the apparently more intrusive character of the process, preserves the appearance and structural integrity of the ancient remains. Once the core sample has been extracted, the only visible alteration is a 10 cm diameter hole, which is immediately filled with inert, non-pozzolanic sand and sealed with a reinserted plug of the original surface material set in a lean lime-pozzolana mortar.

ROMACONS equipment and procedures

The core-drilling rig used in 2002 and 2003 (supplied by Cordiam S.r.l. of Como) comprises a hydraulically-powered drill (model M60-0) mounted on a manually-operated rack and pinion track (Fig. 7). The rack can be mounted onto either a frame built of standard scaffolding tubes or a purpose-built aluminium frame such as that developed for the Project (Fig. 8). A hand-held hydraulically-driven drill (model MAG15) is used to cut small holes in the surface of the concrete for the expanding anchor bolts used to secure the support frame to the ancient structure. The main core drill rotates 10-cm diameter barrels with a diamond-tipped bit. Unlike that used on conventional concrete diamond core-drilling systems, the bit has larger diamonds that form a bracelet around the side as well as on its cutting face. This arrangement is intended to deal with the variety of hard and soft aggregates and mortars that make up Roman concrete. A core-catcher, consisting of a wide, split sleeve with roughened ridges on its interior, is fitted inside the lowest extension barrel, immediately above the drill bit. The sleeve holds the concrete core in position so that it can be lifted out together with the barrels once coring is completed. As the drill bit descends through the concrete, extension barrels of 0.5 m and 1 m lengths (depending on the circumstances) are added in sequence, up to a combined length of 6 m. The hydraulic drill (model LP11P) is powered by a petrol-driven pump connected to it with twin 25 m long, oil-filled, high-pressure hoses with quick-release fittings. A continuous flow of

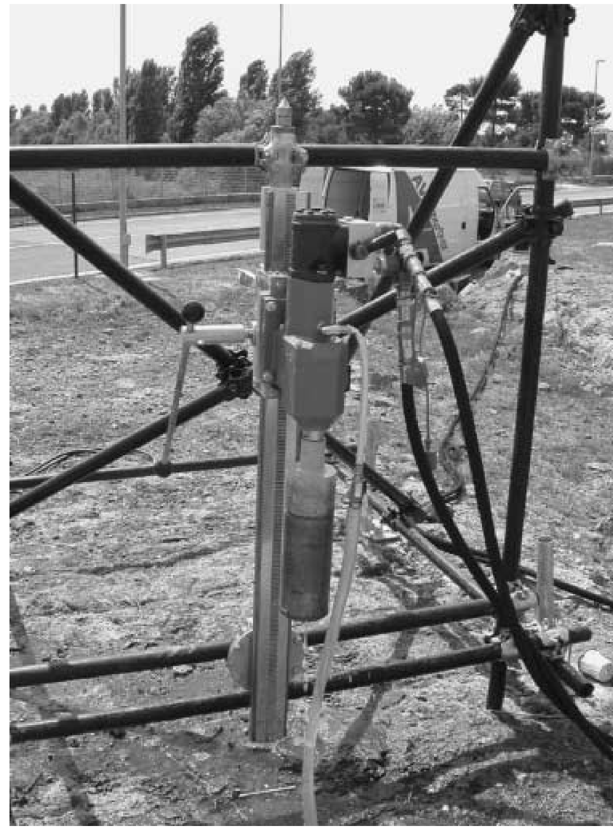

Figure 7. Coring motor and rack, detail.

water is required throughout the drilling process to keep the cutting face of the diamond bit clear of concrete paste and to lubricate the outside of the coring barrels, even when working under water. Quick-release fittings on the drill body channel the pressurised stream of water down the inside of the coring barrels, between the barrel wall and the core, over the diamond bit, and up the outside of the rotating barrel.

At each site where samples are to be taken, the scaffold or frame is positioned to ensure that the rack and pinion is located vertically above the point to be cored. Loose concrete, aggregate or marine growth is carefully removed from around the scaffold or frame in order to provide stable positions for the adjustable feet. These are secured to the concrete with conventional expansion bolts and to the scaffold or frame with scaffold clips. The rack and pinion unit is mounted vertically onto the frame and the drill fitted to it. The hydraulic and water hoses are connected to the drill and the diamond drill bit with a 0.25 m long core-catcher barrel is connected to the drill for the first cut. This initial cut with a short barrel ensures that there is no deflection at the point

Figure 8. Coring device and frame in use at Cosa, Pier 1.

where the bit first cuts into the concrete. After removing the initial surface plug, a 0.5 m long barrel is added and the drilling commenced in earnest. The drill is cranked down the rack and pinion with a hand-operated lever, maintaining constant, even pressure. One operator turns the lever while another adjusts the drill speed and monitors the water flow. As the bit cuts into the concrete it is possible to sense the nature of the material being cored by the resistance to the lever and by the colour of the flushing water, which carries away small particles of spoil.

As the drill cuts down through the concrete, 1 m long extension barrels are added until the drill penetrates through the block into the seabed. A decrease in resistance to movement of the lever and the appearance of fine sand in the flushing discharge indicate penetration of the block. The core is withdrawn by cranking the drill up the rack and pinion gear and removing each barrel in sequence. A removable collar is fitted to each barrel end in turn, above the concrete surface, to ensure that the whole series does not fall down the hole when the drill is disconnected. The concrete cores are tipped out of the barrels into 10 cm diameter plastic pipes and sealed, with the core number, sequence and orientation carefully noted on the outside. Once the core has been removed, the rig is dismantled and the hole filled with inert sand to within approximately 0.50 m of the surface of the block. A weak mix of pozzolana and lime (*c.*4:1) is prepared and trowelled into the remaining section of the core hole, and the surface plug retained from the first cut is reinserted to restore the original appearance. The expansion bolts are removed and the anchor holes filled with the same mortar. The cores are removed from the plastic pipes, studied, measured, and photographed, before the delivery of samples to the various laboratories involved in analysis.

Surprisingly, the actual physical work of setting up the core device under water with SCUBA is easier than on land, because of the beneficial effect of buoyancy during the preliminary work of assembly, which above water requires constant stooping and lifting. The transport and delivery of gear to a submarine coring site, however, is more complicated, and rough weather would make work impossible.

With each field season the ROMACONS team has made improvements and modifications to equipment and procedures. One of the critical issues we are hoping to solve is a method for dealing with cores breaking within the barrel. Due to the uneven mix and the variable hardness of the aggregates and mortar, the diamond bit does not function as smoothly in the ancient concrete as in the modern. The bit occasionally jams and necessitates slight withdrawal of the drill to loosen it. Since the core-catcher locks onto the material in the barrel, the core is fractured at the point of the jam. Unless the whole sample is removed at this stage, any further drilling has the tendency to grind softer portions of the core to paste, since the friction set up within the barrel rotates the freed portion of the core against the concrete being cored. Even without this problem, it may be necessary to remove cores metre by metre, in order to avoid the disintegration of the softer sections of mortar. We have also developed improved expansion bolts for securing the drilling frame to the marine-encrusted surface of semi-submerged or submerged blocks.

Cores and the study of Roman concrete

The primary benefit of taking a core sample is that the core can provide a complete stratigraphic section through a block or slab of concrete from the upper surface through all the layers of aggregate and mortar to the sea bed (Fig. 9). In addition to providing relatively uncontaminated samples of mortar and aggregate from the interior of the block for chemical analysis, this method also supplies uniform, unstressed samples of concrete and mortar which can be subjected to a variety of engineering tests. Based on this promise of new types of information, the ROMACONS team has identified a variety of engineering research questions which complement the historical and archaeological questions noted above. As the database of results expands, there will be an increasingly dynamic and productive interplay between the two data sets. The relevant engineering questions to be applied to all the samples include: sources of the pozzolana and aggregates; proportions of the materials in the mortar mix; ratio of mortar to aggregate; variations in mortar mix or aggregate within a single structure; environment during placement (flooded enclosure or dry cofferdam); method of placement of mortar and aggregate (pre-mixed or layered); evidence for day-joints indicating work stoppage; relation of structure to sea level; nature of sea floor and its preparation for construction; compressive resistance of the concrete, its density and porosity.

Longer-term research goals include the following: comparison of the engineering characteristics of Roman hydraulic concrete with those of modern concrete; determination of the reasons for the resilience and longevity of surviving maritime structures; development of a reliable method for dating the concrete; development of testing and analysis protocols that will enable future investigators and scholars to ask additional research questions without having to resort to additional sampling; development of a database of the chemistry and geological properties of pozzolanic materials from ancient quarries around the Mediterranean; replication of the ancient formwork, materials, and construction procedures in several different situations, in order to evaluate reconstructed work practices, and to obtain data on the rate at which hydraulic concrete mixed according to ancient formulae sets and cures; refinement of the method of sampling the concrete to ensure minimum impact on the long-term integrity of historic structures both above and below sea level; development of a cultural resource management programme that will take into account the research results listed above.

Sampling strategy: Portus, Anzio, Santa Liberata, Cosa

For both logistical and historical reasons the ROMACONS team has begun its fieldwork in Italy (Fig. 2). During the first field season, in late July and early August 2002, coring was carried out at Portus and Anzio (Table 1). During the second field season, in June 2003, samples were collected from a *pila* associated with the fish tank at Santa Liberata, and at the harbour of Cosa

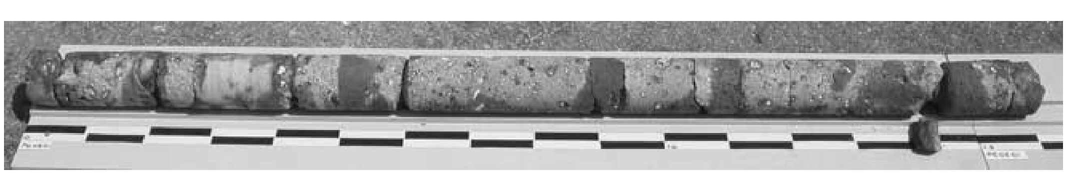

Figure 9. Core POR.2003.01, view.

Table 1. *Statistics for cores taken at Portus and Anzio, 2002*

	POR.02.01	POR.02.02	POR.02.03	ANZ.02.01	PTR.02.01	PTR.02.02
Date	1–2 Aug 02	3 Aug 02	4 Aug 02	6 Aug 02	8 Aug 02	9 Aug 02
Structure	N mole	N mole	N mole	SE b/w	Basin entr.	SW b/w
UTM	4629777	4629726	4629800	4590670	4628837	4628884
Level of top above current sea level	+1.35 m	+2.29 m	+0.07 m	+0.10 m	+1.25 m	+0.16m
Level of top above ancient sea level	+1.85 m	+2.79 m	+0.57 m	+1.5 m	+1.75 m	+0.66 m
Hole depth	1.38 m	3.14 m	1.56 m	3.10 m	2.43 m	1.75 m
Core L	0.26 m	2.80 m	0.45 m	2.25 m	2.23 m	1.65 m
% of core recovered	19%	89%	29%	89%	100%	100%

Table 2. *Statistics for cores taken at Santa Liberata and Cosa, 2003*

	SLI.03.01	PCO.03.01	PCO.03.02	PCO.03.03	PCO.03.04	PCO.03.05
Date	5 June 03	7 June 03	9 June 03	10 June 03	11 June 03	13 June 03
Structure	Piscina pier	Pier 1	Pier 2 S	Pier 2 N	Pier 1.5	Pier 5
UTM	4700418	4697618	4697597	4697597	4697597	
Level of top above current sea level	–0.10 m	+2.11 m	+2.51 m	+2.3 m	–0.12 m	–2.2 m
Hole depth	2.28 m	2.23 m	3.3/3.5 m	3.68 m	1.14 m	0.48 m
Core L	1.50 m	1.65 m	1.60 m	2.25 m	1.10 m	0.48 m
% of core recovered	66%	74%	48%	61%	96%	100%

(Table 2). This selection of sites was intended to provide core samples from a variety of structures: several major imperial harbour installations, an important Republican harbour, and a privately-funded, non-harbour structure. The sequence of sampling also allowed the team to familiarise itself with the equipment and coring procedures initially at structures now on dry land, then on structures at sea level and surrounded by water, and finally on a structure well below sea level. The range of materials, chronology, and structural types has provided useful new information even at this early stage of the ROMACONS Project.

Although new fieldwork is amending our understanding of the chronology and development of the enormous harbour complex called Portus, at the mouth of the Tiber, it still seems likely that the large outer anchorage basin was constructed during the reign of Claudius (AD 54–69), the hexagonal inner basin during the reign of Trajan (AD 98–117) (Fig. 10). Three cores were taken from points spread out along the north mole of the Claudian basin (POR.2002.01–03). It is possible that only a portion of this structure, the north-west end, projected into the sea, while the rest revetted the shoreline of a large basin excavated by Claudius' engineers in what was originally a natural marshy lagoon (Testaguzza, 1970: 52). Two more cores were taken at the same time from a breakwater protecting the canal between the Claudian and Trajanic basins (PTR.2002.01), and from a quay adjacent to the entrance to the Trajanic basin (PTR.2002.02). One core was taken from a large *pila* at the present visible base of the south-east breakwater of the Neronian harbour of Anzio (ANZ.2002.01) (Fig. 11).

In 2003, one sample was taken from the large *pila* just seaward of the north-west corner of the late Republican fish tank at Santa Liberata (SLI.2003.01). An attempt was made to take a second core from a large, isolated *pila* 30 m west, below the Roman villa platform, but sea conditions prevented it. The remaining 2003 cores were taken from *pilae* in the Late Republican harbour at Cosa (Fig. 3): Pier 1 (PCO.2003.01), Pier 2 (PCO.2003.02–03), Pier 1.5 (PCO.2003.04), and Pier 5 (PCO.2003.05). For descriptions of the core samples, see Appendix.

Scientific team, laboratories, and methods

Emanuele Gotti and Roberto Cucitore from the Laboratories of CTG Italcementi Group in Bergamo are carrying out a range of physical tests and chemical analysis on the cores. Charles

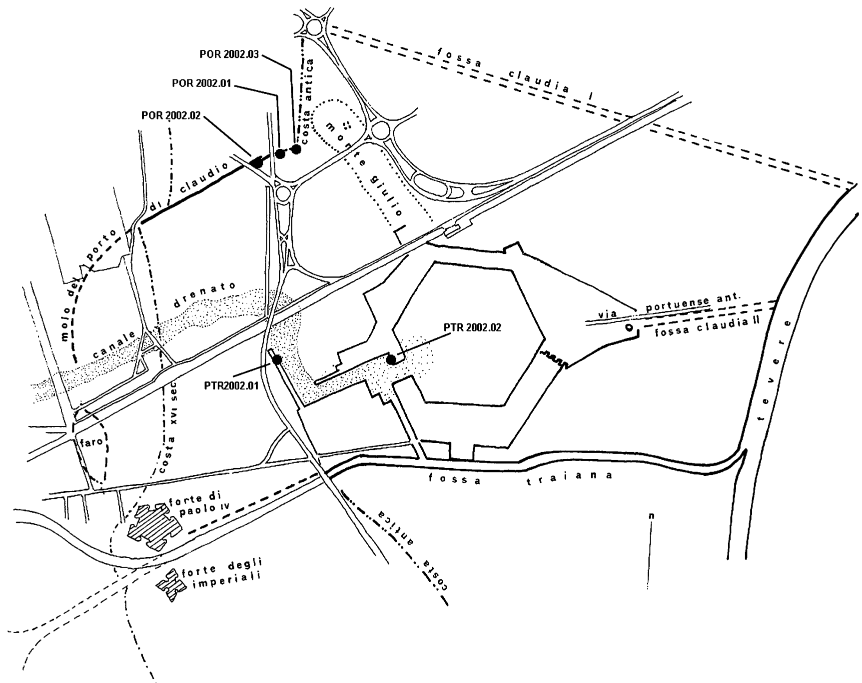

Figure 10. Portus, plan of Roman harbour with indication of core locations.

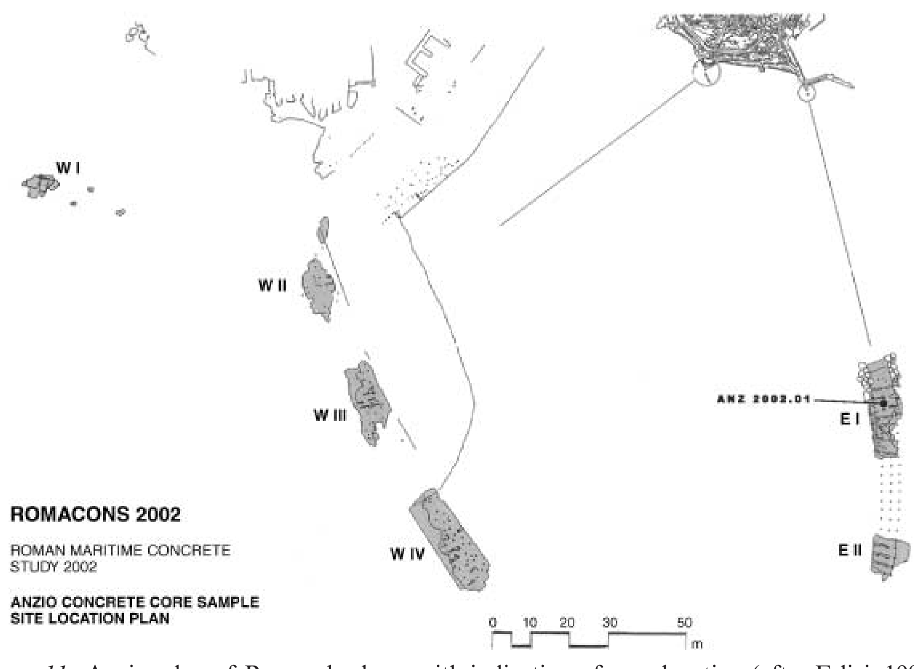

Figure 11. Anzio, plan of Roman harbour with indication of core location (after Felici, 1993).

Stern, at the Department of Geological Sciences of the University of Colorado, is directing some of the chemical and petrographic analysis, and GBG Structural Services, a contract-testing laboratory in the UK, is also involved. Steven Cramer is undertaking the overall interpretation of the analysis and test results. A protocol for the analysis and testing of the samples was established as a minimum requirement to provide a basis on which some of the key questions to the project objectives could begin to be answered. The following procedure has been adopted as a first step and is being reviewed on a regular basis: detailed visual inspection and photographic

Table 3. *Test matrix for cores and subcores*

Cores	Tests on cores	Subcores	Tests subcores or portions of subcores
POR.02.02	Mortar to aggregate ratio	PO2A	Physical, mechanical, porosimetry and diffractometry of mortar
		PO2B	Petrographic examination
		PO2C	
		PO2D	
ANZ.02.01	Mortar to aggregate ratio	A1D	Physical, mechanical, porosimetry and diffractometry of mortar
		A1A	Petrographic examination
		A1B	
		A1C	
PTR.02.02	Mortar to aggregate ratio	PTO2C	Physical, mechanical, porosimetry and diffractometry of mortar
		PTO2A	Petrographic examination
		PTO2B	
		PTO2D	
PCO.03.01	Mortar to aggregate ratio	PCO1A	Porosimetry and diffractometry of mortar, chemical analysis of pozzolana
		PCO1B	Physical, mechanical
		PCO1C	Porosimetry and diffractometry of mortar
PCO.03.02	Mortar to aggregate ratio	PCO2A	Porosimetry and diffractometry of mortar, chemical analysis of pozzolana
		PCO2B	Physical, mechanical
		PCO2C	Porosimetry and diffractometry of mortar
PCO.03.03	Mortar to aggregate ratio	PCO3A	Porosimetry and diffractometry of mortar, chemical analysis of pozzolana
		PCO3B	Physical, mechanical
		PCO3C	Porosimetry and diffractometry of mortar
PCO.03.04	Mortar to aggregate ratio	PCO4A	Porosimetry and diffractometry of mortar, chemical analysis of pozzolana
		PCO4B	Physical, mechanical
PCO.03.05	NA	PCO5A	Porosimetry and diffractometry of mortar, chemical analysis of pozzolana
SLI.03.01	NA	SLI1A	Porosimetry and diffractometry of mortar, chemical analysis of pozzolana

recording of the cores prior to packing for delivery to the testing laboratories; measurement of the percentage of aggregate to mortar; cutting of cores into sub-core lengths after conditioning to 50% RH at 20 °C; measurement of the dynamic modulus of elasticity of the sub-cores; measurement of the compressive strength of the sub-cores; petrographic analysis of sections cut from remains left over from preparing the sub-cores; air void analysis of sections cut from the cores; preparation of the remains of the shattered cores after the compressive tests for SEM and XRD analysis of the binder material, the lime and pozzolana fractions; mercury intrusion porosity testing of the sample fragments; measurement of the composition of the aggregates, particle size, distribution and weights of each fraction; separation of pumice from the fragments analysed to identify major and trace elements using ICP-MS techniques (fragments are also analysed for volatile content); on selected pumice separates, determination of the Sr isotropic composition using isotope dilution mass-spectrometry.

Laboratory analysis of the ROMACONS cores

A series of physical and mechanical tests were conducted primarily at the laboratories of Italcementi in Bergamo, Italy, using a test procedure developed by the authors. These tests included the destructive and non-destructive assessment of various lengths of cores (subcores) 86.5 mm in diameter gathered from three locations in 2002 and two locations in 2003 (Tables 1 and 2). Table 3 itemizes the subcores and the tests completed on each. The physical and mechanical tests included measurements of Young's modulus (the

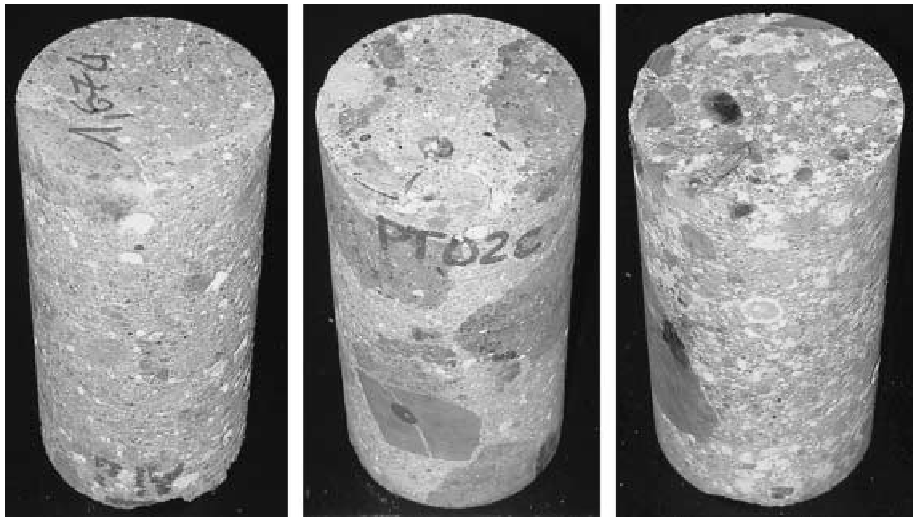

Figure 12. Three 2002 subcores prepared for testing: from left to right, A1D, PTO2C, PO2A.

ratio of stress to strain, a measure of elasticity), compressive strength, density, and porosity. The mineralogical and chemical oxide basis of the mortar and pozzolana were assessed using x-ray diffraction and a scanning electron microscope. In addition, we analysed the mortar and aggregate fractions of the entire length of cores on the basis of digital images. The samples from SLI.2003.01 and PCO.2003.05 were not long enough for this calculation.

The physical and mechanical tests conducted by Italcementi were similar to internationally-established procedures for evaluating modern concrete.[2] Naturally some modifications to these procedures were necessary to accommodate the relatively-limited sample of concrete available. Young's modulus was measured non-destructively in general compliance with ASTM C215. By this procedure, specimens of approximately 175 mm length and 86.5 mm diameter were excited mechanically at their resonant frequency and Young's modulus was back calculated. Compressive strength was measured using the same specimens used in the Young's modulus tests. These were crushed in a hydraulic press and the maximum load recorded in a procedure that generally followed ASTM C39. Density was established through tests to establish the oven-dry mass and the saturated mass to yield a bulk dry density, as described in ASTM C642. Porosity was assessed using mercury intrusion in a manner similar to that described in ASTM D4404 using three or four core fragments and averaging the results. X-ray diffraction was conducted to determine the predominant minerals in the mortar and Italcementi used equipment associated with their scanning electron microscope to assess the pozzolana chemically.

Mortar to aggregate ratios were established by analysing digital photographs of the cores. Digital images of the three selected cores were printed to scale and traced to select and define the areas of binder matrix (mortar) and the aggregate (tuff, other stones, brick, tile etc.) larger than 5 mm in diameter. Three lines were inscribed along the length of the core drawings, one along the central axis and two lines 25 mm either side. The fractions of mortar and aggregate were measured for each line as well as the cumulative totals.

Petrographic examination was conducted by GBG Structural Services of Hertfordshire, England, following ASTM C856. Thin sections were prepared after an initial examination with an optical microscope employing magnifications up to x80. These were then examined with a Leitz multifunctional microscope employing various magnifications up to x8000.

Selection of analytical laboratory results

Three 2002 subcores (Fig. 12), from three different locations, were tested following the procedures described. In the 2003 fieldwork, multiple cores were obtained from the same general site and from these subcores were prepared, and in some instances multiple subcores to assess repeatability. Those used for the mechanical tests were solid, sound, and contained a variety of coarse aggregate sizes ranging from approximately 5 mm to 150 mm.

The results of mechanical property tests are shown in Table 4. Interpretations of these results

Table 4. *Physical and mechanical properties of Roman concrete subcores*

Subcores	Height (mm)	Density (kg/m^3)	Youngs Modulus (MPa)	Compressive Strength (MPa)
PO2	171.0	1583	5560	7.8
A1D	184.0	1549	6440	6.3
PTO2C	176.5	1665	7570	4.9
PCO1B	211.2	1624	7200	7.4
PCO2B	216.6	2163	18,800	9.4
PCO3B-a	214.6	1652	7050	8.0
PCO3B-b	217.2	1587	8750	7.9
PCO4B-a	206.4	1589	6500	5.5
PCO4B-b	215.7	1557	5750	6.4
PCO4B-c	205.2	1635	4850	5.1
PCO4B-d	214.7	1542	6900	5.5
Typical modern portland cement concrete	NA	2325	24,820	27.6

Table 5. *Physical and chemical Roman core properties*

Core	Mortar to aggregate ratio	Subcore	Porosity of mortar	Predominant mineral phases in mortar samples
POR.02.02	1.7	PO2	46.8	calcite, brucite, sanidine, phillipsite, analcime, quartz
ANZ.02.01	1.9	A1D	49.0	calcite, brucite, sanidine, phillipsite, analcime, quartz
PTR.02.02	1.9	PTO2C	52.0	chabazite, sanidine, diopside,calcite, analcime, hydrocalumite, quartz
PCO.03.01	2.2	PCO1A	42.3	calcite, microcline interm., quartz, augite, biotite
		PCO1C	43.6	orthoclase, analcime, sanidine, kaolinite, biotite, leucite
PCO.03.02	1.3	PCO2A	35.1	quartz, calcite, sanidine, kaolinite, tobermorite, augite
		PCO2C	37.1	montmorillonite, quartz, calcite, microcline interm., augite
PCO.03.03	3.4	PCO3A	44.7	calcite, quartz, microcline interm., augite, leucite, tobermorite
		PCO3C	45.8	montmorillonite, quartz, calcite, sanidine, augite, biotite
PCO.03.04	1.4	PCO4A	48.4	quartz, calcite, sanidine, augite, biotite, kaolinite
PCO.03.05	NA	PCO5A	51.3	montmorillonite, quartz, calcite, microcline interm., augite, leucite
SLI.03.01	NA	SLI1A	46.5	quartz, calcite, sanidine, augite, tobermorite, hydrotalcite

are hampered by two limitations. First, by modern standards the overall sample size and that for specific locations are extremely limited. Care must exercised in interpreting the data. Second, comparison based on the original or expected properties of the concrete is obviously not possible, and thus the impacts of time and deterioration cannot be separated from these results. Nonetheless, these are some of the first published values of the mechanical properties of Roman harbour concrete, and they allow several observations.

By modern standards, the Young's modulus and compressive strength values are quite low, only 1/4 that of current Portland cement concretes (Table 4). The unit weight (density) is about 2/3 that of modern concrete. Mortar to aggregate ratios (Table 5) revealed a tendency to use higher proportions of mortar compared to modern concretes, which exhibit a ratio of mortar to aggregate (by weight) close to 1. Porosity values in the Roman concrete are several times greater than those of modern concrete. The properties are consistent in that low Young's modulus, low strength, low unit weight and high porosity are likely to occur together. Despite the relatively low properties, these concretes have exhibited an extraordinary level of durability, as evidenced by the age and condition of the subcores (Fig. 12).

Considering the range of values in Table 4, there is no immediate explanation for the unusually high properties of subcore PCO2B. Visual examination reveals nothing unusual about this subcore other than a more uniform gradation of aggregate sizes, so further analysis is warranted. If the PCO2B outlier is ignored, the coefficient of variation (standard deviation divided by the

Table 6. *Chemical analysis of pozzolana for 2003 cores*

	PCO.03.01	PCO.03.02	PCO.03.03	PCO.03.04	PCO.03.05	SLI.03.01
SiO_2 (%)	59.64	58.63	59.44	59.16	58.71	57.35
Al_2O_3 (%)	19.12	19.48	19.85	19.53	19.36	19.35
Fe_2O_3 (%)	4.07	5.05	4.21	5.00	5.02	5.44
CaO (%)	5.71	3.83	3.60	3.96	3.66	4.90
MgO (%)	0.71	1.01	0.89	1.29	1.00	1.23
Na_2O (%)	2.62	2.17	2.22	2.19	2.25	2.15
K_2O (%)	7.54	9.21	9.14	8.36	9.27	8.74
TiO_2 (%)	0.59	0.61	0.65	0.51	0.72	0.83

mean) for the entire data set is 17% for Young's modulus and 19% for compressive strength. The degree of variation within a single core can be assessed from the results of PCO4B; the coefficient of variation in Young's modulus for this one core is 15% for Young's modulus and 10% for compressive strength. The degree of variability within a single site (with the exception PCO2B) was essentially the same as that among all the sites.

These values clearly suggest that essentially the same mix design or different mix designs yielding similar overall properties were achieved from site to site. The multitude of different mix designs used in modern construction would result in much larger variability if randomly sampled. The variability from core to core (and probably from batch to batch) is a bit higher than modern standards, suggesting that proportioning and mixing were probably not highly refined processes.

Petrographic examination of thin sections derived from the 2002 cores revealed crushed coarse and fine aggregates in a lime matrix with scoria and volcanic materials present to act as pozzolans. In all cases, microscopic examination revealed well-mixed and distributed constituents with no obvious defects. Cracking was present in all samples but the concrete was sound with no obvious deterioration mechanisms. Secondary deposits were present including ettringite (indicating a source of sulphate?), especially in the cores from Anzio, but—though often associated with distress in modern concretes—these did not produce distress in the Roman concretes. Perhaps the relatively high porosity allowed deposits to form but did not allow them to impose internal stresses which would lead to distress and cracking.

The predominant mineral phases of the mortar derived from x-ray diffraction for samples from all locations are shown in Table 5 in the order of predominance. They are characterised by the presence of calcium carbonate (due to binder carbonation), quartz, feldspars (microcline, orthoclase, sanidine), feldspathoids (leucite), pyroxens (augite), zeolites (analcime, chabazite), mica (biotite), and clay minerals (montmorillonite, kaolinite). Differences in the relative predominance of phases are present but could be due to the small size of the samples and different alteration of pozzolana caused by environmental conditions. On the basis of these spectra it is plausible that pozzolana additions are of the same nature for all the samples. Previous testing on samples of the mortar and tuff from piers at Cosa has shown that the pozzolana came from the Bay of Naples region, while the tuff ('Volsinian') was imported from an inland site north-east of Cosa (Gazda, 1987: 76 n.5; Trigila in McCann *et al*., 1987: 313–14). Table 6 shows the chemical breakdown of pozzolana samples from the 2003 cores. The comparable values clearly indicate the similarity from core to core and between the two sites.

Generally, the test results show remarkable consistency among locations. The packing of particles displayed and the lack of voids indicates a care in construction suggesting that concrete was consolidated during placement, rather than simply poured or dumped into position. Variability in properties among different locations was slightly greater but generally in line with variability within an individual core. It is difficult to believe consistency between locations would be so uniform without a purposeful plan and quality control of the labour-intensive process.

New light on Roman maritime hydraulic concrete

The concrete in core SLI.2003.01 resembles that of the cores recovered in 2002. The mortar from the Cosa harbour, however, provided some surprises. In the first place, both the pozzolanic and non-pozzolanic portions of cores PCO.2003.02–03, and the pozzolanic mortar of PCO.2003.04–05, contained a significant proportion of local beach sand. Beach sand does not appear in PCO.2003.01, but perhaps the sample is atypical. The use of beach sand in pozzolanic mortar is not mentioned by Vitruvius or other ancient authors, and not yet documented elsewhere, suggesting that this may have been an early formula later discarded. Preliminary observation of the Cosa cores suggests that this concrete is significantly harder than that at Santa Liberata. The hardness of concrete is not necessarily linked to its durability (pers. comm. E. Gotti), and the harbour installations investigated by ROMACONS up to this point seem to have survived despite being constructed of a soft mortar. Clearly the mortar used in the *pilae* of the imperial period was largely suitable for that application. The engineer planning construction of the *pilae* at Cosa (and perhaps the entire lagoon complex) clearly understood the value of using pozzolanic mortar and tuff aggregate in sections of those structures near or below sea level. But, given the relative newness of this technology, perhaps he assumed that the hardness and density given by sea sand would be just as important for hydraulic structures as for terrestrial structures. Although the Cosa piers and walls appear to have survived very well, it may be that later experience suggested to Roman engineers that the use of pozzolana without beach sand provided a better mix, or was easier to prepare.

In addition, the cores taken at Cosa reveal that there is no weathered or even distinct seam between the pozzolanic and non-pozzolanic mortars, indicating that the piers were built in one construction phase. The C14 dating of carbonized wood found in the upper portion of Pier 1 (noted above) suggests that construction should be dated to the second or third quarter of the 1st century BC, rather than to the later 2nd century BC.

Formwork design and construction procedures

The results of the visual and laboratory analyses of the ROMACONS cores, combined with observation of the traces of formwork recorded during the fieldwork, have begun to yield important data on construction procedures and formwork design. These data, in turn, can allow tentative calculation of labour requirements and cost for Roman harbour structures. Although a full account of the evidence for formwork around Roman maritime structures cannot be attempted here, several points can be clarified on the basis of the ROMACONS research. The wooden formwork prepared for Roman maritime structures was intended principally to contain the mortar and aggregate while they were being placed, and to protect the semi-liquid concrete mass from waves and currents until it had set (Oleson, 1988; Felici, 1993; Brandon, 1996; Brandon, 1997; Felici, 1998; Brandon, 1999). Occasionally, the formwork may have been intended to serve as a long-term exterior cladding for the structure. The exposure of the site to currents and swells would have greatly restricted the periods when work could proceed. In the Mediterranean, unless the site was naturally well protected, construction operations would have been limited to spring and autumn, when sea conditions were normally calm. Hydraulic concretes had the advantage of setting relatively quickly under water, so the formwork did not have to deal with significant hydrostatic loads or withstand the forces of the sea and the load of setting concrete for long. The formwork or parts of it were also used as a working platform and scaffold for the labourers and mortar troughs and materials as well as providing moorings for the barges.

Vitruvius (5.12) describes three methods for casting concrete structures in the sea, one of which (quoted above) involves the placement of hydraulic concrete inside a flooded form. Given the variability of the marine environment and the great variety of Roman structures built in the sea, even Vitruvius must have known that he was providing only a generic description. In reality, local conditions and traditions, intended function, and economic constraints dictated specific designs. The formwork unit had to be sized and shaped appropriately to allow the concrete to be built up layer by layer in a controlled manner and to the proper design, but the evidence collected so far indicates almost infinite variation in size, design, and finish. The size of forms (and thus the extent of a pour) shows the most variation, for example: Cosa, Pier 5, 4.8 × 4.3 m; Caesarea, Area G, 15 × 11.5 m; Anzio, east mole, 8.5 × 6 m; Santa Liberata, *pilae*, 9 × 7.7 m and 11.1 × 8.7 m.

The depth of water in which the Romans were routinely willing to place concrete appears to have been 4.5 to 5 m (as at Santa Liberata), and the maximum depth so far known is 10 to 11 m (as at Nisida). Gianfrotta claims that the Nisida *pila* was cast in a double-walled watertight form, since the exterior of the structure appear to show traces of *opus reticulatum* facing (Gianfrotta, 1996: 71). The construction and de-watering of a form of this depth for such a purpose, however, seems difficult and unnecessary. Beyond 10 m, or even 5 m, preparing a level site for the formwork and concrete would have presented problems, as would assembly or construction of the formwork and its protection from wave action. Greater depth would also have made it very difficult to lower the baskets of mortar and stone aggregate with any accuracy or efficiency, and difficult to level or compact the material from the surface with long-handled tools, or with divers. Finally, the sheer amount of material needed to fill a deep form and to produce a structure such as the *pila* at Santa Liberata (*c.*420 m^3) seems to have pushed logistical capabilities to the limit.

Erection of stable formwork for a concrete structure must have been an exacting task. At some sites, such as the west mole at Anzio or the canal exit at Monte Circeo, the formwork design, reconstructed on the basis of impressions in the concrete (Felici, 1993), seems chaotic and jerry-built, as if the contractors made up the design as they went along. At Cosa, Portus, and Astura, on the other hand, the forms were fairly regular in design and measurement. At Caesarea Palestinae, the engineers hired shipwrights to construct barge-like formwork that could be floated into position and sunk before being filled with carefully-differentiated layers of hydraulic and non-hydraulic concrete (Oleson, 1988; Brandon, 1997; Brandon, 1999). The simultaneous consideration of site location, formwork design, and characteristics of the concrete will shed new light on Roman harbour engineering.

Logistics, time, and costs are an essential part of this picture. DeLaine's comprehensive analysis of the construction and economics of the Baths of Caracalla (1997) has established a methodology for estimating the workforce, time and expense of building concrete structures in the Roman era, whether terrestrial or in the sea. All aspects of the building process can be described in terms of labour, transport and fuel. One of Delaine's propositions is that for most Roman buildings the raw materials used in their construction had very little intrinsic value, a factor that would be particularly noticeable for moles and *pilae* built with hydraulic concrete. The location of the building materials and the consequent cost of transporting them to the site was crucial to the overall economics of terrestrial building projects and represented a significant proportion of the total cost (DeLaine, 1997: 216–17). Harbour construction had a significant advantage in this regard. Pozzolana, the key raw material for marine structures could be easily shipped from the harbour at Puteoli to maritime sites anywhere in the Mediterranean. The lime, aggregate, and lumber could be shipped economically in the same way. Is it possible that this relative advantage accounts in part for the early and rapid advances in Roman harbour construction and the spread of this technology around the Mediterranean?

Evidence for the costs of shipping bulk cargoes such as pozzolana is scanty and tenuous. DeLaine's estimates were based for the most part on Diocletian's Price Edict, which mentions only volume and distance rather than type of cargo, although wheat is probably assumed (DeLaine, 1997: 210). In consequence we are not attempting at this stage to establish the costs of maritime concrete structures, but instead the sequence of procedures, the time it took to build them, and the quantities of material and the labour needed. The outer *pila* of the *piscina* of Santa Liberata is a useful, relatively straightforward test example, and the results can be used to make some reasonable estimates for the whole *piscina* and for other similar structures in the same region.

The northerly, outer *pila* at Santa Liberata is one of the largest known Roman concrete structures cast in the open sea. Quadrangular in plan, with sides measuring 8.9, 9.0, 7.7, and 7.6 m and over 5.9 m tall (volume 420 m^3), it was laid in water approximately 4.5 to 5 m deep (currently over 6 m). The irregular outer *pila* at Nisida is even larger, measuring $7.7 \times 14.2 \times 9.02 \times 15.2$ m in plan, and 9.5 m tall (volume over 1100 m^3) in water *c.*11 m deep, but the details of its construction remain problematic. The major stages of work that must have been involved in building the *pila* at Santa Liberata can be reconstructed as follows:

Quarrying limestone chunks (probably locally), cutting fuel for the kiln and burning in a lime kiln.

Stockpiling of quicklime at the nearby beach, slaking and ageing for three months before use (DeLaine, 1997: 175–6, 189).

Felling trees (probably nearby on the Monte Argentario) and shipping timber to the construction site.

Cutting and shaping lumber for upright pilings, tie and cross beams, and planked 'sheet' piles.

Table 7. *Labour needs (based on the calculations in DeLaine, 1997: 123, 176, 268)*

Task	Unskilled labour	Skilled labour
Production of 152 m^3 of slaked lime from 57 m^3 of quicklime	68 man-days unskilled	7 man-days supervision
Filling and carrying	272 man-days unskilled	
Mixing mortar (415 m^3)	228 man-days unskilled	23 man-days supervision
Erecting formwork (assumed to be 3 times the rate for land site)		21 man-days skilled
Laying concrete in form	206 man-days	21 man-days
Total	774 man-days (1.84 man-days/m^3)	72 man-days (0.17 man-days/m^3)

Because of the special application, heavy, unseasoned lumber would be preferable.

Preparation of baskets and ropes for carrying and placing mortar and aggregate, and long-handled rakes for spreading and tamping the mixture.

Quarrying of pozzolana and tuff aggregate near Puteoli and transport to site (pozzolana must be used soon after quarrying, see Vitruvius, 2.4.3, 'within three months'; DeLaine, 1997: 189).

Underwater site preparation, possibly involving removal of boulders by divers to expose the sandy bottom, or deposit of a gravel bedding layer.

Constructing formwork, driving support piles, setting cross- and tie-beams, driving in timber 'sheet' piles for the sides.

Building a working platform adjacent to or above the formwork.

Levelling of the sea floor within the form, unless already completed; possibly also bracing of the footings by piling rocks against the exterior.

Preparation of stiff mortar mix on shore, transfer of mortar and aggregate to formwork on barges.

Placement of mortar and aggregate (separately?) by lowering baskets with tip ropes to the base of the enclosure.

Spreading and compacting of mortar and aggregate mix by labourers standing on the cross-bracing or scaffolding above sea-level, operating long-handled rakes.

After setting and initial curing of the concrete over several days, removal of exterior planking for re-use. Vitruvius (5.12.4) assumes that a block of lime mortar cured for two months on land is sufficiently strong to be tipped into the sea. Pozzolanic concrete cures more quickly and after two months a block poured underwater would have been ready for the addition of superstructures.

Approximately 65% (273 m^3) of the total volume of the Santa Liberata *pila* consists of mortar and 35% (147 m^3) of large aggregate, mostly tuff. It is interesting that DeLaine (1997: 123) has calculated almost the exact reverse of this ratio for the Baths of Caracalla. There is a significant volume change when loose, dry pozzolana and lime are mixed together with water to form a mortar and then compacted within the formwork. DeLaine (1997: 123) estimates this to be in the order of a total reduction of 66% of the volume of the loose, dry materials. Therefore, to make 273 m^3 of solid mortar requires 415 m^3 of dry material mixed in the Vitruvian proportions of two units of dry pozzolana (277 m^3) to one (138 m^3) of slaked lime. Allowing for 10% wastage, the overall quantity of materials required is 162 m^3 of tuff aggregate, 305 m^3 of pozzolana and 152 m^3 of slaked lime.

The 273 m^3 of mixed mortar is the equivalent of 10,500 2-modius baskets (each 0.026 m^3). In addition, if each basket held two blocks of aggregate with an approximate size of $0.35 \times 0.35 \times 0.075$ m, the 162 m^3 of tuff would have occupied approximately 8000 baskets. DeLaine (1997: 184) calculated for the Baths of Caracalla that one basket could be laid every 4 minutes per man. As it is more difficult working in the sea, it is reasonable to take a rate of one basket every 8 minutes per man. Assuming that it would have been feasible to position labourers at 2 m intervals, then up to 16 unskilled workers could be actively filling the form at any one time. With this workforce, it would have taken 13 days to fill the form, while a further 18 labourers mixed the mortar, and additional men unloaded and transported the raw material out to the site (Table 7). These results all seem reasonable.

Conclusions

Although still in its early stages, the ROMACONS Project has yielded significant results. The innovative sampling technique has been shown to be effective and relatively straightforward, even when applied to structures at or well below sea level. The team successfully cored structures up to 3.68 m thick, and the equipment appears to have the capacity to take cores in the vicinity of 6.0 m in length. The loss of portions of the core through internal grinding can be largely eliminated by removing the core from the tube whenever its integrity has been compromised by backing up the core tube from a jam.

Analysis of the cores has confirmed that the Roman engineers were fastidious about the character and quality of their raw materials and the effectiveness of their procedures. The structures studied so far have all made use of pozzolana imported from the Bay of Naples, probably from the region around Puteoli, just as Vitruvius specifies. It appears that the pozzolana has been sifted to provide significant uniformity in maximum grain size. Although the exact ratio of pozzolana to lime in the mortar of the cores remains to be determined, it is clear that the mortar was very carefully measured and mixed. The aggregates were also carefully selected and sorted by size, and the ratio of mortar to aggregate remains very uniform throughout each structure, except for the base, where there was sometimes puddled mortar without aggregate (see Appendix). The type of mortar and aggregate could vary within a single structure, as at Cosa, where the upper portions of Piers 1 and 2 were built with non-pozzolanic mortar and mostly limestone aggregate and potsherds, and the lower portions were built with pozzolanic mortar and tuff aggregate. The same procedure can be seen at Caesarea Palestinae.

One surprise at Cosa was the identification of significant quantities of local beach (non-pozzolanic) sand in use in the pozzolanic mortar of several piers (PCO.2003.02, 03, 05), even in Pier 5, which must have been completely submerged in antiquity. Given the present status of the harbour structures at Cosa as the earliest known examples of pozzolanic mortar, it is possible that the use of both pozzolana and beach sand in a single mortar mix represents a formula for hydraulic concrete that predates the distinct hydraulic and non-hydraulic formulas presented by Vitruvius. Another surprise was the relative weakness and porosity of Roman concrete compared with modern concretes. Nevertheless, although weak, the concrete obviously is remarkably durable in the maritime environment, very probably more durable than its modern equivalent. The Roman engineers undoubtedly recognized the limits of the material and responded by over-engineering their structures, both in the sea and on land.

With the possible exception of Piers 1 and 2 at Cosa, at least the lower portions of all the structures sampled were most probably poured in forms filled with water. The lower end of two of these cores (ANZ.2002.01, PTR.2002.02) consists of water-sorted particles of lime and pozzolana, without aggregate, possibly the remains of an initial pour of mortar alone, intended to seal any fissures at the bottom of the form. None of the structures sampled revealed any obvious evidence for long pauses in the pours, not even between the different types of mortar in the Cosa piers or the two different coloured mortars in the Anzio pier. The core from Santa Liberata revealed a layer of puddled mortar 0.78 m below the top surface, and the core from Pier 1.5 at Cosa revealed a similar layer 0.6 to 0.7 m below the top surface. The absence of day-joints does not have to indicate that the structures were completed in one long, unbroken work session, which would in any case have been logistically very difficult given the number of man-hours involved. The pier at Santa Liberata, for example, would have required approximately 13 days to complete if 16 men worked at the form around 12 hours a day (with proper support on land, see Table 7). If teams worked 24 hours a day without any loss of efficiency, the continuous pour would still have taken nearly a week. It is likely that the rougher working face and the longer curing time of Roman hydraulic mortar in comparison with modern concrete makes detection of day-joints more difficult, and the joints themselves less hazardous to the structure.

The remarkable homogeneity of the concrete and the relative absence of voids indicate that the material was compacted during placement. Presumably the entire area within the form was filled with mortar (by lowering and dumping baskets) to a depth more or less equal to the average diameter of the aggregate. A measured number of baskets of aggregate, calculated to correspond to a desired ratio with the mortar, could then be tossed into the form with some attempt at complete coverage. The workers then raked the work face level and tamped the mix down with long-handled tools. Alternatively, the mortar and aggregate were mixed on the surface and the completed concrete lowered in baskets, before levelling and tamping.

Finally, by documenting the thickness of the structures, the cores taken so far have provided useful and often puzzling information about foundation levels and relation of the harbour structures to sea level. It is often assumed that Roman harbour structures were surrounded by water sufficient to float a large ship (*c.*2 to 3 m depth). In fact, comparison of the level of ancient erosion notches at Portus with the coring results reveals that the foundations of the structures tested at Portus were very close to sea level (see Table 1). Assuming a rise in sea level of approximately 0.5 m since antiquity, even the large pier at Anzio was built in relatively shallow water, and Piers 1, 1.5, and 3 at Cosa must have been constructed on the ancient beach. Further sampling of harbour structures may force us to change our conception of how Roman engineers planned their harbours, and the role that the seemingly massive walls and piers were intended to play.

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Notes

1. Translations from Greek and Latin are by J. P. Oleson.
2. Standards cited in this section include the following: C215-02, Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens, ASTM Book of Standards Volume 04.02; C597-02, Standard Test Method for Pulse Velocity Through Concrete, ASTM Book of Standards Volume 04.02; C39/C39M-03, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM Book of Standards Volume 04.02; C642-97, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, ASTM Book of Standards Volume 04.02; D4404-84 (1998)e1, Standard Test Method for Determination of Pore Volume and Pore Volume, ASTM Book of Standards Volume 04.08; C856-02, Standard Practice for Petrographic Examination of Hardened Concrete, ASTM Book of Standards Volume 04.02.

Appendix—Physical description of ROMACONS cores

In the following abbreviated descriptions of materials, the colour definitions are taken from the Munsell Soil Colour Charts. The descriptions of the cores proceed downward from the top surface of the block ('0.0').

POR 2002.01. Taken at mid-point of north mole, 7.5 m east of the road leading to the main Leonardo da Vinci Airport terminals, 1.9 m from south face of the mole, 3.7 m from north face (33T0271604. UTM 4629777). Problems with water supply limited coring depth to 1.38 m. One core fragment 0.11 m long was recovered from *c.*–1.0 m, along with fragments from above –1.0 m totalling *c.*0.15 m long. The intact sample was fairly hard and compact, but much of the block may consist of fairly poor cement, since it disintegrated during sampling.

Depth (m)	Mortar	Aggregate
c.–1.0	Hard, off-white with very mixed, pebbly, grey, brown, red, and black micro-aggregate with a few small lime nodules; sorting of micro-aggregate is not uniform, but the mortar on the whole is well mixed.	Brown (10YR 5/3) and strong brown (to reddish) (7.5 YR 4/6) tuff.

POR.2002.02. Taken from large concrete mass farther west along north mole, 14.27 m east of road to restricted military area, 10.26 m from north face of mole (33T0271508. UTM 4629726). Testaguzza identified this mass of concrete as remains of the lighthouse foundation poured inside the great barge of Caligula (1970: 105–11). No wood from a hull was retrieved with the core, suggesting that his proposal is incorrect. Three solid core sections were retrieved: L 1.58 m (0.00 to –1.58 m), L 0.40 m (–1.58 to –1.98 m), and L 0.82 m (*c.*–2.32 m to –3.14 m). This section of the breakwater consisted of good quality concrete, but with pockets of softer cementing materials.

Depth (m)	Mortar	Aggregate	Other
0.00 to –0.40	Off white, consisting of small rounded grains intermingled with bits of grey and brown tuff and numerous lumps of lime of various sizes; very poorly mixed, but hard.	Fine-grained, light yellowish brown tuff (10YR 6/4), containing occasional black crystals, and numerous inclusions of slightly more red tuff.	
–0.40 to –0.73	Very hard, light grey (2.5Y 7/1, or Gley 1 7/N), containing rounded, coloured particles of pozzolana, along with numerous big and small lumps of lime (diam. 1 mm to 15 mm), grey tuff, and pumice.	As above.	
–0.73 to –0.86	More crumbly, with many lime lumps, some pozzolana granules, and crystals of gypsum.	As above.	
–0.86 to –1.38	As above. From –1.00 to –1.38 m, the mix is *c.*80% mortar, 20% aggregate	As above. Occasional fragments of charcoal, and rope or basketry reeds	
–1.38 to –1.98 (Fig. 13)	As above. Contains a few large fragments of charcoal (up to D 0.015 m), and one carbonized fragment of a reed or stick. The last 0.15 m of this sample consists entirely of mortar.	As above. Once piece of very hard light brown (10YR 8/2) sandstone aggregate, a few pieces of a very hard, very fine grained brown (10YR 5/3) tuff (?) with numerous fine black crystals.	
–1.98 to –2.32	A stratum of loose, limey mortar washed away during coring.		
–2.32 to –3.14	As above.	As above.	Original lagoon (?) floor reached at – 3.14 m, extremely fine grey brown sand with numerous black specks.

Figure 13. Core POR.2002.02, *c.*–1.60 to –2.0 m.

POR.2002.03. Taken at a low section close to east end of visible portion of north mole, immediately north of Museo delle Navi, 3.84 m from south face of mole, 1.29 m from north face (33T0271688. UTM 4629800). This portion of the mole is a thin and very poorly-constructed concrete wall laid directly on sand, possibly only the footings for a masonry wall meant to form the quay or retaining wall to hold back the backfill as the harbour basin was excavated. The structure seems undermined at several points, and the heavy, coarse sand underneath suggests a regime involving wave action. It is possible that the sand was introduced as the harbour breakwaters disintegrated and the wave action undermined this wall. The concrete was very soft and easily ground up during the coring process, so a core hole 1.56 m deep yielded two pieces of concrete totaling only 0.36 m long, probably originating from the upper part of the block.

Depth (m)	Mortar	Aggregate	Other
0.00 to –1.00 (?)	Crumbly, light brownish grey (2.5Y 6/2), well-mixed, containing nodules of pozzolana, numerous small grey, yellow, green, and white lumps of tuff and pumice up to D 0.008 m, and a few small lumps of lime.	Hard, strong brown (7.5YR 5.6) tuff with slightly redder inclusions and grey inclusions.	
–1.56			Sea bed: coarse grained, off white sand with numerous heavy black particles.

ANZ.2002.01. Taken from middle of large *pila* at base of southeast breakwater at Anzio, adjacent to modern parking lot, 10.99 m from northwest corner of the block; 12.09 m from northeast corner (33T0302127. UTM 4590670). The core barrel penetrated to a depth of 3.10 m, approximately 0.60 m below the base of the block. It is likely that approximately 0.25 m of limey pozzolana at the bottom of the core was lost to the drilling activity. The last 0.60 m consisted of a very compact deposit of grey-green sea sand, which remained accessible to a tape-measure even after the coring tube was withdrawn.

There seem to be three series of pours in this core: 1) a pozzolana-lime mix dumped without aggregate (unless the core sample is incorrect) directly on the sea floor (–2.25 to –1.90 m). Much of this layer separated in the water and did not form a solid cementing substance. 2) a very consistent layer of carefully mixed concrete 1.63 m thick (–1.90 to –0.27 m). 3) above –0.27 m the mortar has a different colour, resulting either from weathering, percolation of sea water into the hardened concrete mass, or the use tuff additives from a different source. This last pour probably followed immediately upon the second, given the absence of laitance or other indication of settling.

Depth (m)	Mortar	Aggregate	Other
0.00 to –0.27	Well mixed, light olive brown (2.5Y 5/4); very granular with numerous small fragments of yellow (2.5Y 7/6) fibrous tuff or pumice and occasional lime nodules; rounded grains of pozzolana hydration products.	Olive brown (2.5Y 4/4, moist; light yellowish brown when dry, 2.5Y 6/4) tuff.	
–0.27 to –1.90	Well mixed, light grey (10YR 7/1), numerous lime nodules (D 0.003 m to 0.01 m) and many fragments of gray tuff (up to D 0.01 m. Two less compact lenses of mortar around –0.90 m and –1.80 m.	As above.	
–1.90 to –1.94 (Fig. 14)	Water separated layers of extremely fine, grayish white lime particles with a distinct upper boundary.	None.	
–1.94 to –1.99	Very fine greenish-grey pozzolana with greenish hue.	None.	
–1.99 to –2.04	Coarse greenish-grey pozzolana, with much lime.	None.	
–2.04 to *c.*–2.25	Loose mix of greenish grey (Gley 1 5/10Y) pozzolana and poorly mixed lime, retrieved from the tube in crushed form. Thickness of deposit *c.*0.30 m.	None.	
–2.25 to –3.10			Coarse, greenish grey sea sand with numerous black grains.

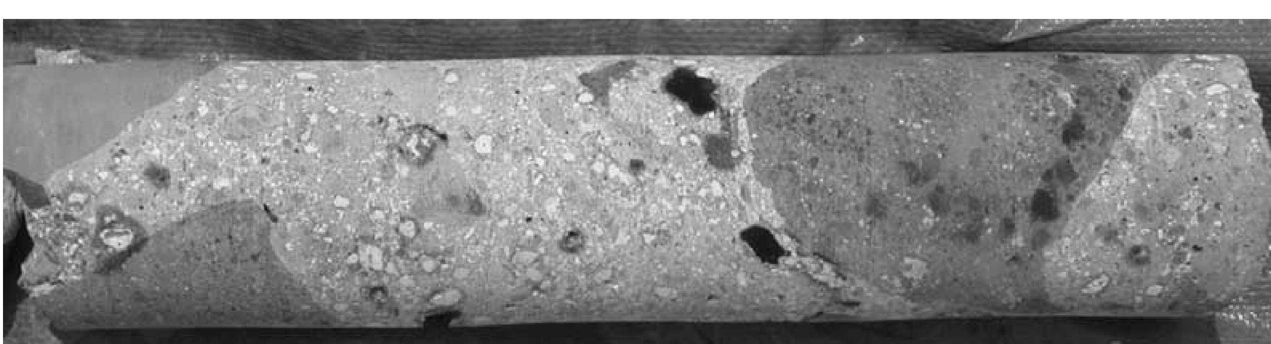

Figure 14. Core ANZ.2002.01, –1.80 to –2.25 m.

PTR.2002.01. Taken 40 m south of present north end of mole protecting west side of entrance channel from the Claudian to the Trajanic basin, 2 m in from east face of mole (33T0271623. UTM 4628837). The core hole was drilled to depth of 2.43 m, 0.2 m into the sea sand, yielding a core L 2.23 m. The core is quite uniform, consisting of well mixed mortar and uniformly sized and spaced chunks of tuff aggregate. There were occasional brick fragments, and one 'levelling course' of brick at –1.15 m. The block was founded on a fine, possibly lagoonal sand.

Level (m)	Mortar	Aggregate	Other
0.0 to –0.27	Reddish brown, speckled with red, yellow, green, and grey pozzolana granules (to D 0.005 m), and a few lime nodules. The mortar seems weathered, softer and with looser grains than that deeper in the block.	Very hard, very fine-grained, yellowish brown (10TR 5/4) tuff with occasional black specks; several fragments of brick.	
–0.27 to –1.10	Hard, well-mixed, off-white (10YR 8/1), with heavy admixture of grey pozzolana particles and occasional lime nodules.	Light grey (2.5Y 7/2) to dark brown (10YR 4.3) tuff, some of it speckled with coloured scoriae; fragments of light red brown (2.5YR 6/3) and very pale brown ('light yellow', 10YR 7/3) brick (Th 0.022 m, 0.035 m).	
–1.10 to –1.12			'Leveling course' of one light red brown (2.5YR 6/3) brick (also seen on face of mole.
–1.12 to –2.0	Same concrete mix as above.	Same concrete mix as above.	
–2.0 to –2.23	As above, but softer and less well mixed, with seams between many of the granules.	Two large amphora sherds.	
–2.23 to –2.43			Fine, light brown sea sand.

PTR.2002.02. Taken near west edge of north-south quay wall in front of 'Severan warehouses', just north of the entrance to hexagonal Trajanic basin, in a modern excavation pit surrounded by a wooden fence (33T0272140. UTM 4628884). Core tube was drilled to depth of 1.67 m below the upper surface, *c.*0.1 m into the original sand bottom, yielding a core L 1.65 m. The core is quite uniform, consisting of well mixed mortar and uniformly sized and spaced chunks of tuff aggregate, similar to that of PTR.2002.01. At least the first portion of the pour was laid in an inundated form on sand subject to wave action.

Depth (m)	Mortar	Aggregate	Other
0.00 to –0.20	Light yellowish brown (*c.*2.5Y 6/3) with large pozzolana granules and occasional lime nodules. The mortar seems weathered, softer and with looser grains than that deeper in the block.	Very speckled red to brown tuff that appears to be almost a conglomerate, and a yellowish red (5YR 4/6) speckled tuff.	
–0.20 to –1.40	As above, but unweathered, greyish white (10YR 8/1, 9/), well mixed, with darker grey pozzolana granules to D 0.005 m.	As above.	
–1.40 to –1.65	A layer of chalky, light greenish-grey (Gley 1 8/10Y) lime (Th 0.05 m) above water-sorted granules of light greenish grey (Gley 1 7/1) pozzolana, the heavier particles deeper than the lighter.	Two pieces of yellowish red tuff at the bottom of the pour.	
–1.65 to –1.85			Coarse, dark grey sea sand with numerous black particles.

SLI.2003.01. Taken from centre of *pila* just off the north-west corner of the piscina at Santa Liberata (32T0688713. UTM 4700418). Core tube was drilled to depth of 2.28 m below the upper surface, *c.*0.10 m into the original sand bottom, yielding a core L 1.50 m. This was a hard, well-mixed concrete, which possibly preserves traces of a day joint at –0.78 m.

Depth (m)	Mortar	Aggregate
0.0 to –0.20	Greenish grey to dark greenish grey in colour (Gley 1 6/N to 5/10Y), consisting of rounded grains of grey-green pozzolana, occasional inclusions of calcite (?), and many white lumps of lime (D ≤ 0.015 m).	Irregular chunks (D ± 0.10 m) of yellow brown (10YR 5/6 to 4/4) tuff containing many lighter, yellow inclusions of fibrous pumice and grains of a hard black mineral. The tuff fades to a greenish tinge near its junction with mortar. One piece of very hard and fine-grained limestone aggregate.
–0.20 to –1.2	Mix of mortar and tuff as above. Higher proportion of tuff from –0.20 to –0.75 m, then higher proportion of mortar to –1.10 m.	
–0.78 (Fig. 15)	An uneven, irregular layer of finer particles of mortar may indicate a pause in the pour.	
–1.2 to –1.5		A mix of tuff fragments, most likely because the mortar was ground away here by the coring device, reducing the core by 0.7 m.

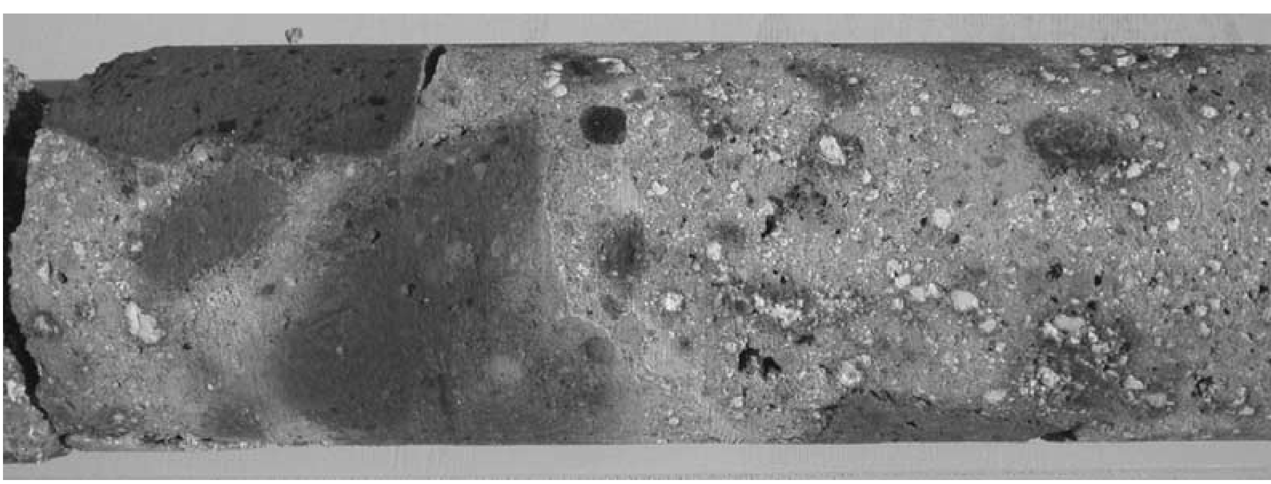

Figure 15. Core SLI.2003.01, area around –0.78 m.

PCO.2003.01. Taken from Pier 1 at Cosa harbour, on the modern beach (32T0688713. UTM 4697618). Coring hole depth was 2.23 m, yielding a core of very uniform, well-hardened concrete recovered in several long sections (L 1.65 m). This pier, like Piers 2 and 3, appears to be the result of one sequence of construction, even though limestone aggregate was used for the top 0.5 m, and tuff aggregate below. The differentiation in aggregate may indicate that the upper portion of these piers was out of reach of the sea water, although the mortar appears to be the same throughout. One fragment of charcoal (D 0.01 m) at –0.35 yielded a C14 date of 2020 ± 40 B.P., giving a range of 57 BC to AD 33 (TO-11233). The core sample terminates with tuff crumbled during the sampling procedure. The concrete in the lower portion of the pier may have been poorer in quality.

Depth (m)	Mortar	Aggregate
0.0 to –0.5 (Fig. 16)	Very hard, fine-grained, light greenish grey to dark greenish grey (Gley 1 7/N to 7/10Y), well-mixed, but containing many small white nodules of lime (D up to *c.*0.01 m; most <D 0.005 m), small tuff fragments, occasional small voids (D *c.*0.003 to 0.02 m), and occasional small fragments of ceramic. In contrast to the other PCO samples, the mortar in this pier apparently did not include beach sand along with the pozzolana.	Irregular, light grey (Gley 1 8/N to 7/N) chunks of limestone (D ≤ 0.10 m).
–0.50 to –1.30	As above, but possibly slightly more fine-grained.	The same yellow brown (10YR 5/6 to 4/4) tuff seen in SLI.2003.01 and the other Cosa samples, containing large black grains and yellow fibrous pumice inclusions. This is Volsinian tuff, from a source 60 km northeast of Cosa (Gazda, 1987: 76 n. 5). The proportion of aggregate seems quite low, perhaps only 10 percent. There is no obvious seam at the point where the limestone and the tuff aggregate concretes meet, but the lower mortar is slightly more yellow brown than elsewhere in the sample, perhaps as a result of laitance.
–1.30 to –1.65	As above, but contains larger lumps of lime (<D 0.03 m), and there are irregular voids up to D 0.03 m.	

Figure 16. Core PCO.2003.01, *c.*–0.40 to –0.60 m.

PCO.2003.02. Taken from the south end of the top of Pier no. 2 (32T 0688720. UTM 4697597). Depth of the core hole from the top of the pier to the top of the beam hole is 2.10 m, 2.38 m to bottom of beam hole, *c.*3.50 m to bottom of pier. The core sample (L 1.60 m) was damaged as a result of the difficulty in coring through one of the horizontal holes left by the formwork beams. The core is intact from –0.05 to –0.50 m, but the section from –0.50 to –0.70 m was lost during the sampling process. Section –0.70 to –1.60 m is broken but complete.

Depth (m)	Mortar	Aggregate
0.0 to –0.95	Very hard, sandy, light grey in colour, with a large proportion of rounded beach sand (as in PCO.2003.03, 05), consisting of black, clear, and green grains, many lime nodules (D ≤ 0.005 m), occasional fragments of ceramics, and occasional small voids.	Amphora sherds (hard, sandy, reddish yellow fabric, 5YR 6/8), with grey limestone and occasional chunks of beachrock and Volsinian tuff.

Depth (m)	Mortar	Aggregate
–0.95 to –1.50	Very hard, grey-blue, with pozzolana grains, a significant proportion of beach sand, and occasional fragments of ground up ceramics. The pozzolanic mortar below –0.95 m is slightly darker than the mortar above, but there is no apparent seam. Possibly the two types of mortar were intermingled at this point.	Chunks of limestone, beachrock and an occasional potsherd.
–1.50 to –1.60	As above.	Tuff as above.

PCO.2003.03. Taken from north end of top of Pier no. 2 (32T 0688720. UTM 4697597). Core hole was 3.68 m deep to base of the pier, yielding an excellently-preserved, 2.25 m-long core.

Depth (m)	Mortar	Aggregate
0.0 to –0.10	hard, sandy, light grey in colour, containing a large proportion of local beach sand, consisting of black, clear, and green grains (as in PCO.2003.02,05), numerous lime nodules (D ≤ 0.005 m), and occasional small voids.	Hard, sandy light reddish brown (2.5 YR 6/4) amphora fragments.
–0.10 to –0.50	As above	Grey limestone.
–0.50 to –2.25	Hard, sandy, light grey, pozzolana, with a significant component of rounded beach sand, small lumps of tuff, and frequent lumps of lime (D ≤ 0.01 m). This mortar is slightly darker in colour and slightly finer in texture than the non-pozzolanic mortar above, but no obvious seam separated the two types, perhaps because the pours of mortar were mixed at this point.	Volsinian tuff, small fragments of limestone, and occasional small fragments of ceramic.

PCO.2003.04. Taken from middle of Pier 1.5, a low platform connecting Piers 1 and 2.

Depth (m)	Mortar	Aggregate
0.0 to –0.15	Very hard, light grey (1 Gley 7/N) to grey (1 Gley 6/N), with many lime inclusions, poorly mixed and varying from D 0.001 to 0.015 m, and several voids and inclusions, particularly at –0.45 m. The mortar takes on a greenish tinge in proximity to the aggregate.	Volsinian tuff as above, but coloured greenish grey (Gley 1 4/1 10GY) by reaction to the pozzolana in the presence of infiltrated water.
–0.15 to –1.10 (Fig. 17)	As above.	Volsinian tuff, preserving its typical yellow brown (10YR 6/6) colour, and containing fibrous brownish yellow (10YR 6/6) pumice inclusions and black specks.
–0.40	Several irregular voids up to D 0.02 m.	
–0.60 to –0.70	A layer in which the particles have been water-sorted by size, forming a thin stratum of fine particles, perhaps a day joint.	

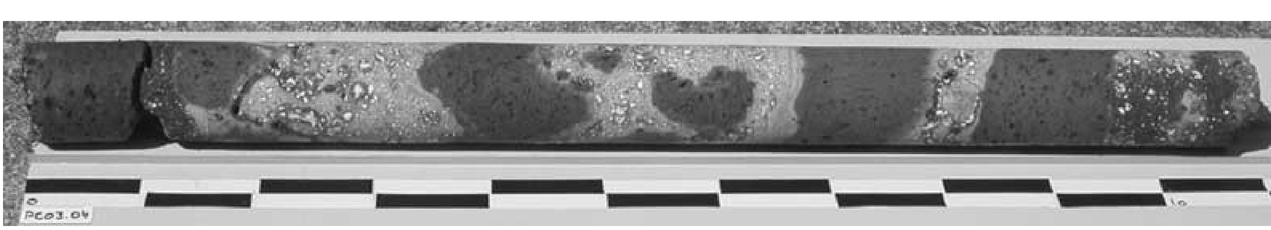

Figure 17. Core PCO.2003.04, view (0.0 at left).

PCO.2003.05. Taken from southwest edge of Pier 5. Because of the friable nature of the outer surface of the pier, it was not possible to anchor the coring frame securely, and coring had to be terminated at –0.48 m.

Depth (m)	Mortar	Aggregate
0.0 to –0.15	Soft, dark greenish grey (Gley 1 4/5GY), containing many pozzolana grains, a significant proportion of grains of beach sand (black, clear, and green; as in PCO.2003.02, 03), and many lumps of lime (D ≤ 0.007 m).	Volsinian tuff, coloured a dark greenish grey (Gley 1 3/1 10Y) by the sea and the mortar, containing inclusions of a fibrous pumice and hard, dark specks. At –0.15 m a fragment (L 0.07 m) of hard, sandy, light red (2.5YR 6/6) amphora ware and one fragment of limestone.
–0.15 to –0.50	As above, but lighter greenish grey (Gley 1 7/10Y) and harder in consistency.	As above, including one fragment of limestone.

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