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Notes

The Concrete Construction of the Roman Harbours of Baiae and Portus Iulius, Italy: The ROMACONS 2006 field season

The development by the Romans of hydraulic concrete for use in coastal underwater structures probably originated somewhere in the vicinity of Baiae (modern Baia) and Puteoli (modern Pozzuoli) at some time before the last quarter of the 2nd century BC (Oleson *et al.*, 2004: 199–203). The earliest surviving hydraulic concrete found to date is the harbour *pilae* at Cosa, dated between the late-2nd century and the mid-1st century BC (Gazda, 1987: 155 n.84; 2001: 163; Oleson *et al*., 2004: 202; Gazda, 2008; McCann, 2008). Roman hydraulic concrete consists of large irregular stone or tuff aggregate set into a mortar of lime and sand-like volcanic ash rich in chemically-reactive aluminosilicates. The bibliography on Roman hydraulic concrete is extensive, with most relevant published works listed by Gazda (2001: 171–7) and Oleson *et al.* (2004: 228–9, 2006: 51–2).

The main ancient literary source which refers to concrete and its use in maritime structures is Vitruvius, *De Architectura* (2.6.1, 5.12.2–3), but there is a scatter of useful shorter comments in Strabo, Pliny, and Dionysios of Halikarnassos (see Oleson *et al*., 2004: 199–203; 2006: 33–4). By direct attribution, or through the implications of the term *pulvis puteolanus* ('powder from Puteoli'), Strabo (*Geography* 5.4.6), Vitruvius (*On Architecture* 5.12.2), Seneca (*Questions about Nature* 3.20.3), and Pliny (*Natural History* 16.202, 35.166) specifically identify the area around Puteoli, the modern Campi Flegrei at the north end of the Bay of Naples, as the source of the volcanic ash. The modern term is *pozzolana*, which in the strict sense should be applied only to ash from this region (see Jackson *et al.*, 2007). The modern term for the resulting concrete is 'hydraulic concrete'. In antiquity, this material was used extensively in coastal defences (protective breakwaters), harbour structures, and fish farms. Unless disturbed by modern shoreline developments, these structures can be very well preserved despite the sometimes harsh environment in which they have survived.

Although none of the early, pioneering structures built of hydraulic concrete in the sea in the Gulf of Pozzuoli (ancient *Baianus Sinus*) seems to have survived, this remains an important area for the study of Roman hydraulic concrete in maritime structures. By the early first century BC this region attracted affluent Roman aristocrats including members of the imperial household, who constructed *villae maritimae* on the shore and *piscinae* in the sea (D'Arms, 1970). During the last decades of the Republic and throughout the imperial period several major military harbours were established, which involved extensive building projects in the sea (Frederiksen, 1959; Scognamiglio, 2006; Miniero, 2007).

The ROMACONS Project

ROMACONS, the Roman Maritime Concrete Study, was established in 2001 to study the development and application of Roman concrete in maritime settings. The project investigates the make-up of the material, its physical properties, and the nature of its placement. Standard core-drilling procedures were adopted in order to take intact stratigraphic samples (0.09 m in diameter and up to 5.8 m long) which are then analysed in the laboratories of Italcementi with a comprehensive set of physical, mechanical and chemical protocols (see Oleson *et al*., 2004: 208–10; 2006: 47–9). Since fieldwork began in 2002, the team has recovered cores at Portus, Anzio, Cosa, Santa Liberata, and Brindisi in Italy, at the harbour of Caesarea in Israel, at the eastern harbour of Alexandria in Egypt, and at the harbour of Chersonesos in Crete. The five cores we recovered

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in September 2006 from the harbour of Baiae and from Portus Iulius in the Gulf of Pozzuoli are the subject of this article.

Along with precise definition of the engineering characteristics of Roman hydraulic concrete, our fieldwork has confirmed that the Roman engineers considered *pozzolana* from the Campi Flegrei as the optimal ingredient for hydraulic concrete in maritime structures both in Italy and elsewhere in the Mediterranean. Large quantities of this material were shipped to Caesarea in Israel, for example, in the last quarter of the 1st century BC (Branton and Oleson, 1992; Hohlfelder *et al*., 2007), and we have also identified Baian pozzolana at the smaller Roman harbour of Chersonesos in Crete (Brandon *et al.*, 2005). In 2004 the team constructed an 8 m^3 experimental *pila* in the harbour of Brindisi using pozzolana from Baia and other appropriate materials. When tested, the resulting concrete produced results very similar to those obtained from ancient concrete (Hohlfelder *et al.*, 2005; Oleson *et al.*, 2006). Since Baiae, Puteoli, and the surrounding area were very probably the birthplace of structural hydraulic concrete and its maritime applications, the region seemed an obvious choice for sampling.

Permission was granted by the Soprintendenza per i Beni Archeologici delle Province di Napoli e Caserta for the team to take cores on the long moles protecting the entrances to the commercial Portus Baianus and the military Portus Iulius, and from a series of large *pilae* in the Gulf of Pozzuoli halfway between the two harbours, now called *Secca Fumosa* ('Smoking Shoals') because of the many submerged fumaroles in the area discharging hot water and gas (Scognamiglio, 2002; Miniero, 2007). The upper surfaces of all these structures once projected several metres above sea-level, but isostatic change of tectonic origin has left them at present around 3 to 4 m below sea-level. The harbour breakwater of ancient Puteoli is now inaccessible beneath the modern breakwater.

Marcus Agrippa constructed Portus Iulius in a rush by during the civil wars at the end of the Republic, around 37 BC (Suetonius, *Life of Augustus* 16; Scherling, 1953). The engineering challenges were enormous, and the achievement so momentous that both Virgil (*Georgics* 2.161–4) and Pliny (*Natural History* 36.125) mention the harbour as one of the man-made wonders of Italy. A fragment of wood from the formwork in the *pila* off the port side mole of this harbour (as one enters) yielded a C14 date of *c*.50 BC (2060 ± 40 BP; TO-13105). The date of the harbour structures fronting Baiae is less well documented, but the town was an important bathing and villa centre from the early-1st century BC, so the moles and breakwater could be even earlier than those of Portus Iulius. The function of the 28 *pilae* spread over an area of 160 × 100 m at Secca Fumosa is not clear (Scognamiglio, 2002: 53–5), but they may have protected a road or the Portus Iulius structures by breaking the force of waves at some distance from the shoreline. Scognamiglio suggests that they supported a lighthouse, or an alternative entrance to Portus Iulius. In either case a date in the later-1st century BC or even later is likely.

A unique type of maritime construction evolved along with the development of hydraulic concrete in the Gulf of Pozzuoli. *Pilae*, large cubes or tall, square piers of concrete were cast on the sea-bed, their upper surface usually projecting above the waves. One of the largest such structures known can be seen at nearby Nisida, with sides of 7.7, 9.02, 14.2, and 15.2 m and a height of over 9.5 m (Gianfrotta, 1996: 71). Such *pilae* were grouped together in a single line (sometimes connected by arches, as at the breakwater at Puteoli) or in two overlapping rows to form discontinuous breakwaters or sea defences for a shoreline or at the entrance to a harbour. Examples of this form of construction can be seen at Miseno, Baia, Secca Fumosa, Portus Iulius, Pozzuoli, and Nisida around the Gulf of Pozzuoli, as well as other sites along the Italian coast, notably Cosa and Santa Liberata, and further afield at Caesarea in Israel and Cherchel in Algeria (Felici, 2006: 59–81). This manner of construction can be clearly seen in the ancient representations of the harbours of Puteoli and Baiae on a fresco at Stabiae and a series of engraved glass souvenir vessels found at various sites around the empire (Ostrow, 1979; Blackman, 1982: fig. 5). Roman designers took advantage of the plastic nature of concrete to cast mooring-stones into some of these large masses, as on a number of the arched mole *pilae* at Pozzuoli, as well as at Nisida and Misenum (Günter, 1903: 272–3; Scognamiglio, 2006: 70–73). Continuous concrete moles, piers or breakwaters were constructed as a line of abutting *pilae*, as at Portus Iulius and Portus Baianus.

It is puzzling that such *pilae* sometimes had sides finished with *opus reticulatum* (a facing of small square blocks forming a net-like pattern) and *opus testaceum* (brickwork), even on surfaces which would have originally been under water, as at Secca Fumosa and Nisida (Gianfrotta, 1996: 71; Scognamiglio, 2002: 54). This finish can also be seen on the submarine sides of the mole at Ponza (Gianfrotta, 2002: 71–3, figs. 5 and 7). It is likely that this facing, invisible beneath the waves, was an attempt to protect the concrete core from erosion. How the Romans laid masonry in regular patterns under water is not clear. Gianfrotta suggests that the blocks with such facing were cast within a double-walled cofferdam which had been pumped dry, but the practical difficulties of achieving this at a depth of at least 6 m in the open sea with the pumps available seem insuperable (Gianfrotta, 1996: 71). The *pilae* which formed breakwaters to harbour entrances, and protected shorelines or maritime villas, were not individually or collectively uniform. Even when clustered together they were of different sizes and often with sides of varying dimensions. They were not even set out regularly, and their spacing and orientation often varied. In contrast, fish-ponds (closed and semi-enclosed) were laid out geometrically, and even the *pilae* which formed the breakwater enclosure to the oyster farm at Pozzuoli were relatively uniform in shape, spacing, orientation and alignment. The reasons for this marked difference in quality between harbour and sea-defence structures and those of fish farms is not readily apparent.

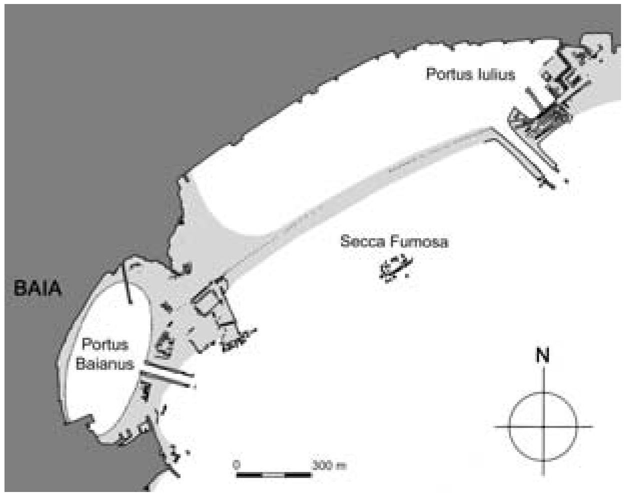

Figure 1. Overall site plan of Baia (Baiae) and Portus Iulius. (C. Brandon after Scognamiglio, 2002)

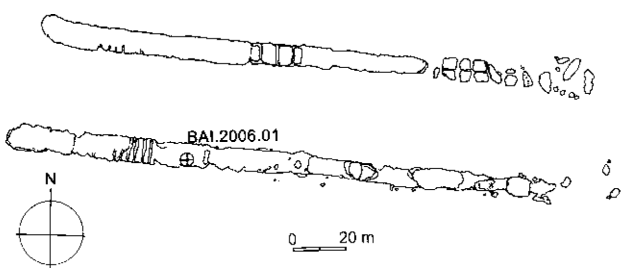

Figure 2. Plan of the entrance channel moles leading into Baianus Lacus. (C. Brandon after Scognamiglio, 2002)

ROMACONS 2006 fieldwork

Between 6 and 11 September 2006 five concrete cores were extracted from the sunken remains of the harbour moles at Baiae (BAI.2006.01), the *pilae* at Secca Fumosa (BAI.2006.03), and from the submerged remains of Portus Iulius (BAI.2006.02, 04, 05) (Fig. 1). The principal objective in taking these core samples was to add to the expanding ROMACONS database of Roman maritime concrete, to enable us to make comparisons between different sites and periods, and to gain knowledge of the development of Roman hydraulic concrete.

The harbour of Baiae was built around a natural lagoon created by a long-dormant volcanic crater now drowned beneath the harbour and marina of modern Baia. Two concrete moles define the entrance channel; the northern mole (to starboard on entering the channel from outside) is 209 m long, and the southern or port mole 232 m long. The moles are approximately 9.5 m wide and define a channel 32 m wide (Scognamiglio, 2002: 48). The core sample BAI.2006.01 was taken from the southern mole (Fig. 2). The concrete is at least 2.3 m thick, the length of the core recovered, although the mole now stands 1 m above the sea-bed. At Secca Fumosa we took a 3-m core sample (BAI.2006.03) from a *pila* which had sides of 9.9, 10, 10.4 and 10.3 m and was over 5.7 m thick with the surface of the block 3.45 m beneath the waves (Fig. 3). There was clear evidence of an *opus reticulatum* finish on the southern face at a depth of 6 m (Fig. 4).

The moles defining the entrance channel leading into the harbour basins of Portus Iulius were similar in design to those at Baiae, although much larger. They are over 220 m long and between 20 and 30 m wide with a channel width of 40 m (Fig. 5). The ends of the moles were defined by a series of large *pilae*, six on the port side (as one enters the harbour) and one on the starboard. We sampled concrete from both entrance channel moles and the outer *pila* on the port side. The concrete was very eroded and the structure broken up; at the site of BAI.2006.02

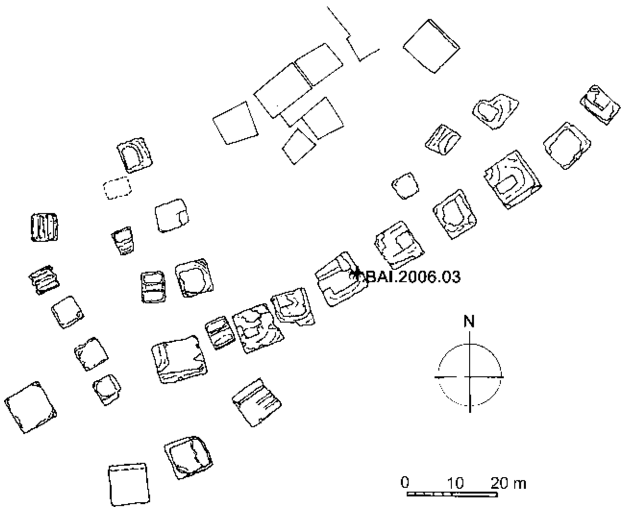

Figure 3. Plan of Secca Fumosa. (C. Brandon after Scognamiglio, 2002)

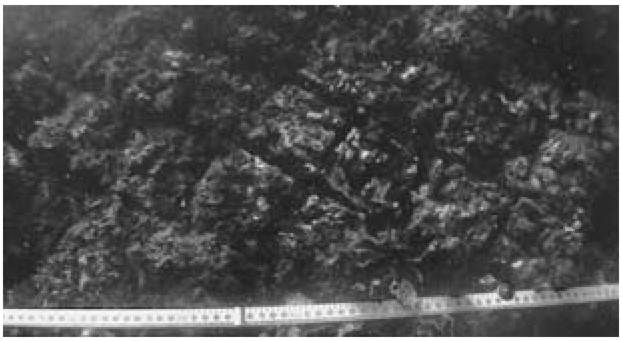

Figure 4. *Opus reticulatum* at a depth of 6 m on the southern face of a *pila* at Secca Fumosa. (C. Brandon)

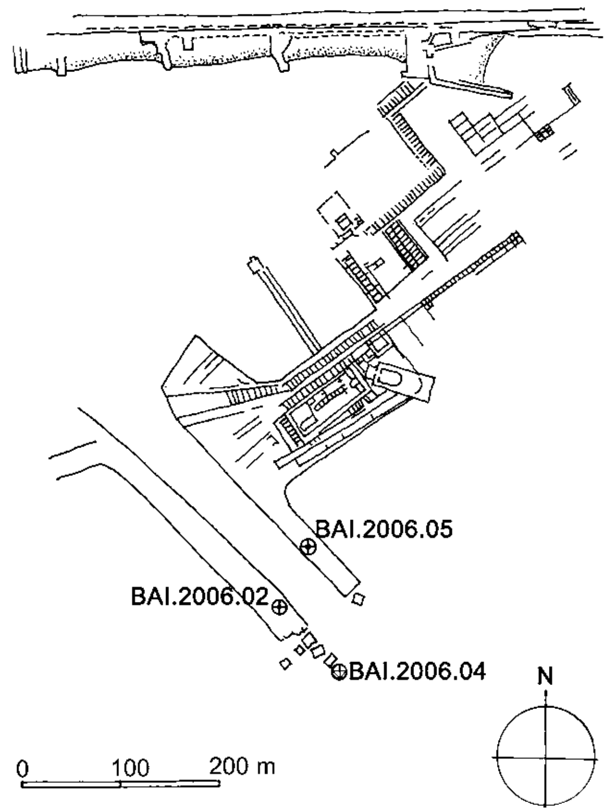

Figure 5. Plan of the entrance channel moles leading into Portus Iulius. (C. Brandon after Scognamiglio, 2002)

on the port side mole it was only 1.6 m thick, and at BAI.2006.05 on the starboard side only 1.5 m thick. The outer *pila* has sides of 10, 10, 11.1 and 9.6 m and an overall height of over 6 m. A 1.5-m-long sample, BAI.2006.04, was extracted from the top, inset section of the *pila* at a depth of 3.8 m.

Analysis

The cores (Table 1) were analysed at the research laboratories of Italcementi in Bergamo. A description of the tests undertaken is included in Oleson *et al.*, 2004: 213–14. Preliminary findings suggest that the concrete used at Portus Iulius was different from that found at Baia, Secca Fumosa and all other sites that we have studied with the exception of Area G at Caesarea in Israel, core CAE.2005.03. Our initial conclusions after studying the Caesarea material was that the concrete had been laid in rough conditions or that the mortar was too wet, resulting in comparatively low levels of CaO and soluble SiO2 and a higher proportion of MgO in the binding matrix (Hohlfelder *et al.*, 2007: 414). Similar levels found in the Portus Iulius cores, BAI.2006.02; 04 and 05 (Table 1) suggest that the builders used too much sea water in the mix rather than being subjected to rough seas, as the chemical composition was consistent across the harbour. Further, more detailed analysis will hopefully be more conclusive as to this significant variation in the chemistry.

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Table 1. *Details of the cores.*

Core BAI.2006	Date taken	Location	Top of core below sea-level	Depth of core-hole	Length of core recovered	Aggregate	Mortar	General
01	06/09	**Baiae**, port side, southern entrance channel mole	5.1 m	2.3 m	2.15 m	local pale yellow tuff, mainly fine and hard but includes many pebbles of up to 10 mm diameter	very variable in consistency and quality, light grey to black; in the lower level appears washed out of the micro-aggregate	a number of large lime nodules of up to 50 mm diameter, and many voids
02	07/09	port side mole, **Portus Iulius**	3.9 m	1.6 m	1.2 m	small aggregate of local tuff		very rough, porous, irregular, very few small lime nodules (appears to have a low lime content)
03	08/09	**Secca Fumosa** *pila*	3.45 m	3.15 m	2.9 m			very uniform, many lime nodules, generally resembling cores from the experimental *pila* in Brindisi harbour
04	09/09	outer *pila,* port side of entrance channel, **Portus Iulius**	3.8 m	3 m	1.63 m (the bottom fraction slipped out of the core-catcher)	very large, irregular aggregate of the local tuff	occasional lime inclusions in the mortar	
05	10/09	Starboard mole of entrance channel, **Portus Iulius**	4 m	1.5 m	1.1 m	large pieces	reasonably good quality, well mixed but appeared to be low on lime	

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Notes

1. For the term *pila* see the glass souvenir flasks of the imperial period from Baiae illustrating the Puteoli breakwater with the inscription '*pilae*' (Painter, 1975; Ostrow, 1979); *CIL* X 1640, 1641, '*opus pilarum*' of the harbour at Puteoli; Seneca, *Letters* 77.1: '*in pilis Puteolorum*'; Livy, *History* 40.51.4: '*pilas pontis in Tiberi*'.
2. Scognamiglio (2002) and others refer to the ancient harbour as '*Lacus Baianus'*, possibly on the basis of Pliny, *Natural History* 14.61: *fossa Neronis quam a Baiano lacu Ostiam usque navigabilem incohaverat* (the ship canal Nero began to dig from the lake of Baiae as far as Ostia). Starting this canal from the small pleasure harbour of Baia rather than the large military harbour of Portus Iulius does not make sense, and in fact both Tacitus (*Annales* 15.42) and Suetonius (*Nero* 31.3) are explicit that the starting point was the nearby Lacus Avernus. Along with the adjacent Lacus Lucrinus, this volcanic

lake had been made into an inner basin for the Portus Iulius. Pliny's 'lake of Baiae' in fact means the 'lake near Baiae', the Lacus Avernus. There does not appear to be any ancient source that refers to a 'Portus Baianus', but this name is likely on the basis of Roman harbour terminology and the local parallel of Portus Iulius.

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