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Reproducing a Roman maritime structure with Vitruvian pozzolanic concrete

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Background: The Roman Maritime Concrete Study

The Roman Maritime Concrete Study, an international research project directed by J. P. Oleson, C. Brandon and R. L. Hohlfelder, was formed in 2001 to study all aspects of the physical and mechanical nature of Roman hydraulic concrete, its employment in the maritime infrastructure of the Roman Mediterranean world, and the sourcing of the various components of this building material during the centuries of use. While our research incorporates relevant historical, literary and archaeological evidence, the main contribution so far has been the development of a technique for the collection, using specialized coring equipment, of large cores from the interior of concrete structures both above and below sea-level. These large, coherent samples can then be subjected to a complete range of chemical and mechanical tests at the research laboratories of the CTG Italcementi Group in Bergamo, which has sponsored some of our research. The research methodology and the specific questions that drive our project, as well as some results of fieldwork conducted in 2002-3 at Antium, Portus, Cosa, and Santa Liberata, have recently been published (Oleson *et al.* 2004b). The project is also amassing a comprehensive data-base that will answer the questions outlined above.[1]

Our results to date have been based on cores taken from surviving Roman structures. Neither these data nor the few passages from relevant ancient sources provide precise information on the procedures Roman engineers used to build formwork in the sea, or to prepare and place the mortar and aggregate components of the concrete in these forms. Vitruvius provides contemporary information about harbour construction but he and other authors (e.g., Pliny the Elder, Strabo) are silent about many mundane though important matters. The literary sources provide no explicit information on such issues as the procedures for measuring and mixing the ingredients of the hydraulic mortar, the use of salt or fresh water, and the methods used to place mortar and aggregate in inundated forms. The project's analysis of cores from ancient structures has now provided reliable information on the strength and constituents of Roman hydraulic concrete, and this article presents data on how quickly the mortar set and how long it took to achieve its maximum strength. We also present data on the process of constructing wooden formwork in the sea, and on the placement of mortar and aggregate.

To collect these data, Brandon, Hohlfelder, and Oleson undertook an experimental project over 9 days in September 2004, during which they constructed a freestanding, 8-m^3 concrete block (*pila* in Latin)[2] in the inner harbour of Brindisi, using only materials and tools that would have been available to Roman builders. A brief, narrative description of this effort has recently been published (Hohlfelder *et al.* 2005); here we provide a more detailed account of this experiment, along with summary analysis of one core taken from the reconstructed *pila*. While we cannot say with certainty that our solutions for construction problems associated with the use of Roman hydraulic concrete mirror precisely the practices of builders two millennia ago, our structure and its materials bear a striking similarity to the ancient *pilae* which our project has already studied.

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1 For discussion of the defects in traditional techniques of sampling and analysis (e.g., by Lamprecht 1996), see Oleson *et al.* 2004b, 204. A project undertaken by Ferreti (1997) focused on conservation shows promise. F. Sear and H. Goldsworthy (University of Melbourne) have recently begun a project that may involve coring of Roman structures on land.

2 E.g., glass souvenir flasks from Baiai illustrating the Puteoli breakwater with the inscription "*pilae*" (Ostrow 1979); *CIL* X 1640, 1641, *opus pilarum* of the harbour at Puteoli; Sen., *Ep.* 77.1: *in pilis Puteolorum*; Liv. 40.51.4: *pilas pontis in Tiberi*.

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