Durability of Ancient Roman Concretes and their Geologic Analogs

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DOE ARPAe Extreme Durability of Cementitious Materials

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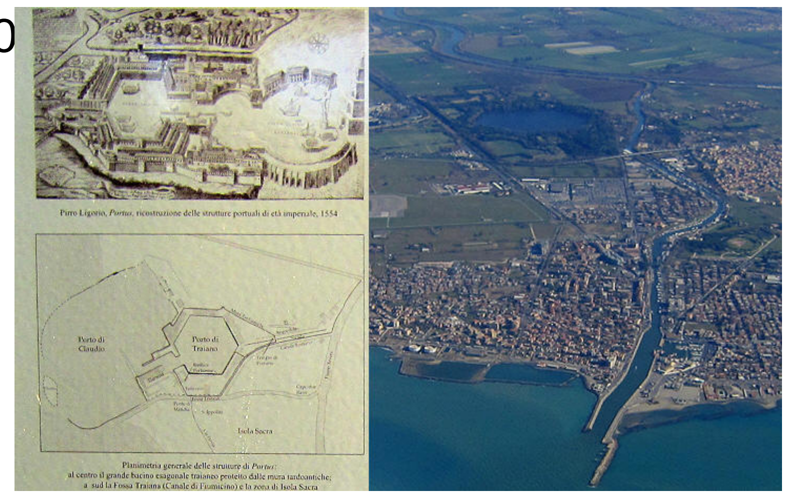
Trajan's Markets, Rome

Trajan, Emperor, 98-117 CE



Trajan's Harbor, Portus

See also: Jackson, M.D., Oleson, J.P., Moon, J., Chen, H., Zhang, Y., Gudmundsson, M.T., in press, Extreme Durability in Ancient Roman Concretes, *American Ceramic Society Bulletin,* June 2018

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Ancient Roman concretes are cementitious materials that gain chemical and mechanical resilience at the millennial scale. This exceptional resilience arises from beneficial long-term responses to chemical attack, and mitigation of microcrack propagation through autogenous growth of mineral cements. The extreme durability of Roman cementitious systems arises from three principal factors. First, early pozzolanic reactions at pH>12 between hydrated lime ($Ca(OH)_2$) and alkali-rich volcanic glass and crystals produced an enduring calcium-aluminum-silicate hydrate (C-A-S-H) binder in a complex mortar that binds decicentimeter-sized coarse aggregate. Full consumption of hydrated lime occurred rapidly in both the marine and architectural mortars. Second, slow dissolution of glass remaining in volcanic particles produced mineral cements through stage III processes (Jantzen et al. I, II 2017). The crystals precipitated from supersaturated fluids derived from floods, ground water, and seawater that percolated through the porous structures and dissolved glass and crystals, becoming progressively more alkaline. The strätlingite, zeolite, and Al-tobermorite cements crystallized in vesicles, interfacial zones, and pores in the cementing matrix. They improve mechanical resilience through increasing fracture toughness and creating new mineral cements along microcrack surfaces. The post-pozzolanic processes have analogies to modern alkali-activated and geopolymeric cementitious systems. Subsequent alteration of cementitious phases produced calcite and vaterite. The third factor in the durability of the concretes is a conglomeratic self-reinforcing framework of volcanic and carbonate rock at the micrometer, millimeter, and centimeter scales.

Roman engineers described foundational principles and installation procedures for the concretes. They described an energetically intensive phase of pozzolanic reaction followed by an energetically self-sustaining phase of post-pozzolanic reaction using analogies with volcanic processes. The active geologic analog for these processes is Surtsey volcano, Iceland, an isolated basaltic island produced offshore of Iceland in 1963-1967. Time lapse drill cores through the still hot volcano in 1979 and 2017 (http://surtsey.icdp-online.org) record the production of mineral cements through beneficial corrosion of basaltic glass and potential biotic activity in environments above and below sea level. Innovative applications of these processes and those of Roman concretes to blended cement and lime-based volcanic rock concretes have the potential to transform current perspectives and practices for the production of extremely durable cementitious materials. The goal is to gain resilience and toughness through energetically self-sustaining cementitious processes and a complex three-dimensional framework of reactive volcanic rock aggregate.

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Roman (and Surtseyan) Concrete Prototypes
Energy Savings and Environmental Sustainability

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1. Substantial reduction of fuel consumption and CO_2 emissions, relative to Portland cement manufacture

2. Conservation of freshwater resources

3. Domestic volcanic rock resources in the United States replace steel reinforcements
   Self-reinforcing, <u>reactive</u> conglomeratic rock framework
   Multiscale (µm, mm, cm) "matrix-engaged aggregate"

4. Long term durability and service life
   Chemical resilience in a porous, permeable cementitious material
   "Beneficial" glass corrosion, "internal curing" in volcanic glass particles

   Self-sustaining production of authigenic platey and acicular mineral cements reinforce a cementing matrix and interfacial transition zones (Jackson *et al.* 2013, 2014, 2017)

   Mechanical resilience, increased fracture toughness (Brune *et al.* 2013)

   Increased ductility, coherence, and self-healing over time

5. Durability predictions validated through historic concrete structures with volcanic aggregates (pozzolans)
   Build community interest and pride in local concrete architecture from 1910-1970 as models for energetically sustainable construction

   Demonstrate "Proof of Concept" prototypes involving interdisciplinary stakeholders

   Engage lime and natural pozzolan producers in real-time "scaling up" of demonstration prototypes

Relevant Publications

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