Background

Researchers, engineers and builders have found great inspiration looking to the world’s longest-standing structures to better understand their use of indigenous materials and the reasons for their exceptional durability, traits often lacking in many of today’s modern buildings. The Roman Pantheon, the Egyptian Pyramids, and the Great Wall of China are examples of superlative ancient engineering that represent valuable resources to educate us in how to use resources wisely while building stronger and more durable structures. Deep research into the methods used to construct ancient edifices like the Roman Pantheon has uncovered valuable information that can precipitate significant advancements in modern building materials science. The Watershed Materials’ research and development staff is committed to understand the rich and valuable heritage of masonry construction and apply time-tested techniques and technologies to state-of-the-art building materials’ design and manufacturing practices, effectively synthesizing age-old wisdom and modernity.

Many modern building materials are characterized by high embodied energies and suboptimal durability.¹ Concrete, the most voluminous manmade material on the planet, is one of the most versatile and effective building materials in use today, but there remain certain shortcomings in its performance and drawbacks to its use that highlight need for improvement.² Specifically, many modern concretes have been shown to demonstrate relatively poor resistance to weathering and chemical attack, largely owing to factors like the corrosion of reinforcing steel, inadequate material selection and mix design formulation criteria and variability in cement characteristics.³ Furthermore, the environmental costs associated with the production of the energy-intensive stabilizers used in modern concretes are significant, mainly in the form of CO₂ emissions. The production of ordinary Portland cement (OPC), the primary binder in modern concretes, is responsible for an astounding 6-7% of global CO₂ emissions.⁴⁵

Studying and building on the successes of the engineers of ancient structures like the Roman Pantheon can provide practitioners today with valuable tools for improving concrete and masonry design and construction practices. Increased use of indigenous materials and the use of geopolymer stabilization in place of standard energy intensive...
OPC stabilization can potentially extend building lifetimes, enhance durability and mechanical performance attributes as well as reduce embodied energies and environmental footprints.

Ancient Roman Concrete

Certain highly-durable ancient Roman concretes have been the subject of much interest and study in recent years, owing to their outstanding resistance to weathering and deterioration and their novel use of indigenous materials. Modern concretes, though exceptional in many respects, often fail to rival the durability of these remarkable materials of old, with some contemporary concretes experiencing significant deterioration in as little as 5 years after being put into service in aggressive environments. Obviously, this is an unsatisfactorily short lifetime in comparison to that of ancient Roman structures like the Pantheon and the Great Hall of the Markets of Trajan that have survived for over 2,000 years, even in marine environments. Owing to shortcomings and phenomena affecting contemporary concrete construction efforts like reinforcing steel corrosion and varying cement composition, the significant deterioration experienced by many modern concretes over short periods of time calls attention to the need to better understand the mechanisms responsible for the exceptional durability of some of the world’s oldest and most resilient structures. Furthermore, modern concretes require the use of high proportions of energy-intensive materials (most notably, OPC) and frequently involve significant transportation costs, while, by contrast, the concretes of the ancient Romans utilized indigenous materials that required minimal processing and had very low embodied energies.

Modern OPC binders require extensive processing including calcination, a process that requires heating quarried calcium carbonate to temperatures in excess of 800 degrees Celsius. In contrast to these unwieldy levels of energy consumption and emissions of CO₂, the builders of ancient Rome used complex cementitious formulations, consisting of indigenous materials, that exhibit exceptional durability while not requiring energy-intensive processing. These novel, geopolymer-like binders developed their strength through complicated chemical interactions including the polycondensation of oligomers that are more nuanced than the simple hydration of calcium silicate found in the hydration of modern OPC.

In today’s markets, OPC is still favored because it is an easy solution. OPC stabilizers can be employed in a range of applications with predictable results, and they do not require intense precision in formulation, production and quality control. Additionally, OPC stabilizers do not require familiarity with regional materials such as pozzolans that are requisites for producing the ancient Roman builders’ brand of stabilizer.

As with many other aspects of modern construction, the cheap and generic solution is preferred. However, increasing awareness of the environmental costs associated with short-sighted construction methods drives the need for reconsidering many of the materials that have become so ubiquitous in our built environment. These trends, together with advancements in relevant technologies, have precipitated a rising interest
in geopolymer stabilization, which shows great potential to benefit modern masonry construction efforts.

A portion of the evidence that has contributed to a deeper understanding of the composition of ancient Roman concretes and the techniques used in their manufacture comes from written records kept by the builders themselves, notably Marcus Vitruvius Pollio, a famed Roman architect, engineer and author. In his multi-volume work *De Architectura*, Vitruvius displays an impressive knowledge of building materials science including the "reactive capacity" of local pozzolanic ashes and aggregates when combined with hydrated lime. A pozzolan is a material, often naturally-occurring, that contains high proportions of silica and is capable of reacting with calcium hydroxide and water to form cementitious compounds. Vitruvius also provides what Jackson et. al. describe as "highly-accurate empirical descriptions" of Roman tuff, pozzolane rosse, travertine building stones and other local pozzolanic materials.\(^7\) Vitruvius is essentially describing geopolymer reactions.

Vitruvius and his peers utilized their understanding of building material science to produce high-quality pozzolanic concretes that were used in the construction of many ancient Roman structures during the Imperial Age (27 B.C. through 3rd century A.D.).\(^8\) The records of these pursuits, kept by these ancient builders, serve as a valuable aid in contemporary attempts to understand their innovative construction practices.

Largely led by materials science researchers like Marie Jackson at UC Berkeley in California, the recent surge in study of ancient Roman concretes has focused predominantly on understanding the mechanisms responsible for the outstanding performance of these materials. In simplified terms, scientists have described the extreme durability of these outstanding ancient Roman concretes as largely resulting from the following aspects of their production:

i) The incorporation of highly-active pozzolanic materials (found in local pyroclastic flow and volcaniclastic deposits and including: kaolinitic clay,\(^9\) Pozzolane Rosse ignimbrite,\(^10\) volcanic ash and pozzolanic aggregates), hydrated lime and other alkali media into concrectious mix designs allowed for the production of amorphous, durable, calcium-aluminum-silicate-hydrate (C-A-S-H) cementitious binders, bearing many resemblances to modern geopolymers. These novel stabilizers derive their strength from complex interactions between alkali and aluminosilicate materials as opposed to the hydration of calcined limestone that is responsible for strength development in OPC systems. Notably, geopolymer binders have gained much attention in recent years owing to their superior durability, as well as to their potential to reduce the embodied energy and environmental footprint of contemporary concretes. These stabilizers, while typically requiring greater quality control than OPC, can provide many benefits over the long-standing “cookie-cutter” solution it presents.

ii) The compaction of concrectious materials in formworks, together with the implementation of low water-to-binder ratios, improved the performance of
the resulting concretes. These processes helped to ensure a dense interparticle arrangement and minimize pore space in the finished materials, ensuring the efficient procession of pozzolanic reactions and contributing to the development of highly durable products.\textsuperscript{11}

iii) Salt-water curing practices are also thought to have aided in the development of exceptional mechanical properties in many ancient Roman concretes. This phenomenon is presumably due to an exothermic reaction which occurs when certain pozzolanic materials and hydrated lime interact with seawater. This process, which produces portlandite and various calcium-silica-hydrate products and increases curing temperature, is known to encourage the efficient development of high-quality C-A-S-H binders.\textsuperscript{12,13} Furthermore, mineralizing actions resulting from alkali-cation reactions occurring when certain pozzolans and hydrated lime are combined with seawater likely benefited the development of C-A-S-H binders, encouraging charge balancing and stability, the irreversible binding of alkali cations and resistance to chemical attack, as well as increasing curing temperatures.\textsuperscript{14} This feature of ancient Roman concretes starkly contrasts modern concretes in which alkali cation and sulfate interactions typically produce detrimental effects and can contribute to premature deterioration.\textsuperscript{15}

Modern concrete and masonry products can benefit from the application of construction techniques and technologies developed by ancient Roman builders. The ancient Romans' careful selection and use of indigenous aluminosilicate, pozzolanic and alkaline materials, as well as their implementation of novel manufacturing techniques including low-moisture content compaction and saltwater curing, allowed them to develop exceptional, highly-durable concretes of low-moisture that did not require the energy-intensive processing of modern concrete products.

Their use of unique alkali and alumina-rich stabilizers required precision in control over numerous aspects of production, including careful mix-design formulation approaches, unique curing regimes and compaction throughout installation. In contrast to this required precision, modern OPC is prized because it can easily be employed in any region without reliance on specialized knowledge or local materials, and because it is easy to use and requires relatively little quality control. However, the ancient Roman builders' brand of stabilizer in many ways demonstrates advantages over the more generic solution presented by modern OPC.

The embodied energy, environmental footprint and durability of masonry can be improved by offsetting the use of OPC with sophisticated geopolymer binders that incorporate regional pozzolanic and aluminosilicate materials. Additional improvements can be found in exploring the specialized production and curing techniques employed by ancient Roman builders including low-moisture content compaction. The viability of these technologies will be further increased by focusing future research efforts on classification and characterization of natural sources of aluminosilicates for geopolymerization as well methods for deriving alkali materials for the production of geopolymer materials from construction wastes. In this way, modern masonry products can benefit from the
application of construction techniques and technologies developed by ancient Roman builders.

**Watershed Materials LLC**

The staff at Watershed Materials LLC is committed to finding solutions to shortcomings in modern construction pursuits, in part through the study of masonry construction’s rich history and the selective application of the most successful innovations from ancient builders and engineers. Watershed Materials advances technologies perfected by the ancient Romans by utilizing sophisticated C-A-S-H stabilizers and by employing low moisture-content compaction and specialized curing processes. Watershed Materials integrates these historic construction techniques with the industry state-of-the-art by implementing proprietary technologies and production processes including specialized stabilization approaches, high-shear mixing, ultra high-pressure, dynamic compression, and high-efficiency curing.

Building on the tremendous successes of Vitruvius and his peers, Watershed Materials LLC is working to enhance the durability of modern masonry materials while reducing their embodied energy and environmental footprint. These benefits are realized by extending building lifetimes, increasing the use of indigenous materials and implementing low embodied-energy processes of materials processing and stabilization.

The National Science Foundation recently funded research by Watershed Materials to study the geopolymerization of natural, unprocessed aluminosilicates. This research represents a significant advancement in geopolymer stabilization technologies as it focuses on utilizing commonly-occurring aluminosilicates as the source of alumina and silica in geopolymer binders rather than the energy-intensive, regionally-limited SCMs typically used in modern geopolymer applications. This innovation has the potential to dramatically expand the range of feedstocks suitable for geopolymerization and reduce the environmental footprint and embodied energy of next-generation geopolymer stabilizers.
The Pantheon in Rome, the world’s largest unreinforced concrete dome, still standing after 2,000 years. Ancient Roman builders developed novel techniques for manufacturing high-performance concretes that demonstrate the ingenious usage of indigenous materials and outstanding durability. Image credit Biker Jun, used with permission of Creative Commons Attribution-ShareAlike 2.0 Generic.
Dr. Marie Jackson with the President and Lab Manager of Watershed Materials LLC at their headquarters in Napa, California.
- A Watershed Materials’ low-carbon masonry unit. This technology represents a hybridization between modern product design and development and innovative formulation and production techniques developed
by the ancient Romans. Watershed Materials’ low-carbon masonry units incorporate pozzolanic fines, are compacted under extreme pressure, and incorporate novel C-A-S-H stabilizers.

References
14 Komarneni et. al. 1985, Tsuji et. al., 1991, Taylor et. al., 1992

Further Reading

Accessible to public:
http://www.academia.edu/1214963/The_toughness_of_Imperial_Roman_concrete
http://ecosmartconcrete.com/docs/trmehta01.pdf
http://www.businessweek.com/articles/2013-06-14/ancient-roman-concrete-is-about-to-revolutio
nize-modern-architecture

Scholarly: