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Study and Analysis of the Manufacture of Roman Concrete ; Uses of Volcanic Ash and seawater in Ancient Roman Concrete; Chaos, Complexity and Order from the Pozzolanic Reaction

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Abstract:- Roman concrete has withstood the ravages of nature for more than two thousand and many ancient Roman structures still stand. The Romans used volcanic ash as a binder for their concrete and seawater as a mixing and caring agent . The addition of seawater and volcanic ash has been a secret recipe for the unique strength and durability of Roman concrete that gets better with age. The way Roman concrete cures and sets is the secret of its solidity and durability. The hydration of Roman Concrete can go on for centuries.

This paper provides the process of manufacture of the modern version of Roman concrete by the addition of volcanic ash as a clinker and the addition of quicklime. It also provides the platform for addition of seawater and production of the durability that shall far exceed the performance of Portland Cement. Furthermore, it explains the advent of Chaos and nonlinearity in concrete production which also produces order in the concrete structure system.

I. INTRODUCTION

The Romans called their concrete opus caementicium ash, a white powder called quicklime, small particles and rock fragments called tephra and water or sea structures exposed to the ocean were in contact with water (on coastal seawalls).

In contrast, modern concrete is typically made up of a mixture of limestone, clay, sand and other ingredients ground and heated at high temperatures .It also starts to break in as little as fifty years.

Seawater reacted with the ingredients of the concrete of Roman structures , creating new and stronger minerals. .Recent research by Admir Masic and colleagues from the Massachusetts Institute of Technology at an ancient Roman city called Privernum near Rome, has revealed, after collection of samples from the site and testing them in a laboratory, that small calcium deposits embedded in the casting ,known as lime lumps or clasts were the clue to the durability and strength of Roman concrete .

The researchers speculated that the Romans may have used quicklime in their mix before setting it with water. Quicklime is widely available and made from burning limestone. The white powder reacts with water during mixing , sparking a chemical reaction generating significant amounts of heat. This prevents the research team, however, found that it was not so , and occurs due to the addition of quicklime , or calcium oxide, which is formed by heating limestone at a high temperature.

The pozzolanic reaction is exothermic .The increased temperature significantly reduces the curing and setting times , accelerating the reaction and allowing for much faster contraction.

When cracks form in the concrete, they travel specifically to the lime clasts which have a higher surface area than the particles in the matrix. When water gets into the crack, it reacts with the lime to form a solution enriched in calcium carbonate, binding the crack together and preventing it from spreading further.[2]

II. ROMAN CONCRETE COMPARED TO MODERN CONCRETE

Roman concrete essentially consisted of volcanic ash, a white powder called quicklime, small particles and rock fragments called tephra and water or sea structures exposed to the ocean were in contact with water (on coastal seawalls).

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III. THE USE OF VOLCANIC ASH IN ROMAN CONCRETE

The Romans used a mixture of volcanic ash and lime to bind rock fragments into mortar . The mortar was then mixed with the aggregate, often chunks of rock, to make Roman concrete. The Roman historian and philosopher Pliny the Elder described underwater concrete structures that became stronger everyday. A pozzolanic reaction is caused by the combination of ash, water and quicklime. Recent research shows that the basic reasons for Roman concrete's self healing and longevity were the ways the Romans mixed their raw ingredients [3], particularly how they used lime, the key component of the mix and volcanic ash, which was pulverized into fine powder, thus maximizing surface area. Remnants of the lime used in the concrete formed the lime reaction clasts which added to the self healing process significantly. The process, called hot mixing, used a variant of lime called quicklime that with water to heat the mortar mix and fashioned chemistries that otherwise would not occur entirely . When concrete cracks, water or moisture enters and the crack becomes wider and spreads throughout the structure . When water enters, the lime clasts dissolve and release calcium ions These recrystallize and repair the cracks. Moreover , the calcium ions can be reset with volcanic components to reinforce the structure. The potential for volcanic ash as a binder to concrete is therefore a significant advance to overall greener and environmentally friendly concrete production. Roman concrete , thus added significantly to environmentally friendly concrete production.

The composition of volcanic ash is primarily a mixture of rock, minerals and glass. The constituent particles are expelled during volcanic eruption from a volcano. The size of the particles are minuscule, being less than two millimeters in diameter. The structure is potted and possesses many holes, thus giving it a low density.

Particles constituting the primary minerals in volcanic ash are also composed of quartz tridymite, cristobalite,the koshir group of minerals, dumite, anhydride, k-feldspar, biotite , nutile, garnet, pyrite and spectite.

A natural process occurring in the opening of the volcano, produces lime and forms concrete like rocks by mixing it with ash - the same volcanic ash that the Romans used.

The addition of ash in Roman concrete production prevented cracks from spreading.

High temperatures can be produced from the exothermic reaction.by using quicklime . Slaked lime is sometimes used in addition or by itself .

Not mixing, but another factor, research has now established, was actually the key to the super durable nature of Roman concrete.

By testing Roman concrete samples, subjecting them to an x-ray synchronous at Lawrence Betkeley National laboratory in Berkeley, California and mapping outcome locations of minerals , researchers came up with amazing results .They found a silicate mineral called phillipsite , which is common in volcanic rocks, with crystals of aluminum tobermorite , a rare mineral with cation exchange. capacities which has been recognized in lime clasts of the concrete. Al tobermite also occurs in the outskirts of feldspar fragments, a constituent of volcanic ash and its production is similar to basaltic tuffs. The rock and water reaction causes the long term durability of the concrete, based on Pliny the Elder's conclusions.

IV. THE USES OF SEAWATER OR WATER IN THE PRODUCTION OF ROMAN CONCRETE

Modern concrete structures in water crumble within decades, yet two thousand years old Roman piers and breakwaters stand even today. Roman concrete may have gotten , in fact , being even stronger than when they were constructed two millennia ago. Geologist Marie Jackson and her colleagues at the University of Utah have studied Roman concrete [4]and have found that seawater falling through the concrete leads to the growth of interlocking minerals that provide the concrete with added strength and durability.

As mentioned before, The Romans made concrete by mixing lime with volcanic ash and seawater to make a mortar and then adding to that mortar chunks of volcanic rock which served as the aggregate in the concrete . The combination of ash, water and quicklime provides what is called a pozzolanic reaction , named after the city Pozzzouli in the Bay of Naples.[5]The Romans may have gotten this idea from naturally cemented volcanic deposits called tuffs that were common in the area , as described by the Roman historian Pliny the Elder.

Roman concrete was used extensively in building structures, including the Pantheon and Trajan's market in Rome. Huge marine structures protected harbors from the open sea and served as extensive anchorages for ships and warehouses.

Although rock aggregates are also used in the production of modern concrete there is an important difference. In modern concrete the constituents, which are sand and gravel particles are not reactive. Any reaction within will expand and crack the concrete . This alkali silica reaction is common all over the world .and is one of the primary causes of destruction of Portland cement concrete structures, according to Jackson.

Jackson and her colleagues have studied the factors that made concrete in Rome so durable.

Jackson and her colleagues studied the factors that made Roman concrete so resilient. The research group has realized that the mineral growths such as Al-tobermorite and phillipsite prevent cracks from spreading , while the surfaces of non reactive aggregates in modern cement do the opposite, that is, cause cracks to spread [6]

Jackson and her colleagues were the first group to find the rare minerals Al-tobermorite and phillipsite which were produced and helped prevent cracks from spreading in Roman concrete.

Through a pozzolanic reaction at somewhat elevated temperatures mineral crystals of Al-tobermorite formed. The presence of these crystals was a surprise for Jackson and her research team, as synthesizing them in the laboratory requires high temperatures and produces only small quantities.

It was evident from experience that the pozzolanic curing process of Roman concrete was temporary . Only the Romans had produced tobermite at about twenty degrees Celsius.

Geologists are familiar with the fact that structures change internally with natural conditions. The question that can be posed is, how does change influence the durability of Roman concrete?

The research team concluded that when seawater penetrated through the concrete in break waters and piers it disbalanced components of the volcanic ash and allowed the highly alkaline leached fluids, particularly Al- tobermite and phillipsite. The former has silica rich compositions, similar to crystals which form in volcanic rocks. The crystals have platelike shapes that strengthen the cementing matrix. The interlocking plates increase the cement's resistance to brittle fracture.

The above mentioned corrosion process would not be a good thing for modern concrete materials, according to Jackson. We are looking at a system that would be contrary to anything we would desire in cement based concrete. We are looking at a system which thrives in open chemical exchange with seawater.

The procedure for making Roman concrete was long lost. Even now, the precise methods for mixing the marine water to fully recreate the concrete remains unknown . The Romans were observant and realized that volcanic ash grew canals to produce the tuff. These types of rocks don't exist a lot in the world, so there would have to be substitutions made.

The research group feels that while researchers have answered many questions about the mortar of the concrete, the long term chemical reactions in the aggregate remain unexplored. Jackson intends to continue the work of Pliny and other Roman scholars who worked diligently to discover the secrets of their concrete. Building concrete in the sea would require many problems yet to be solved.

V. THE APPEARANCE OF CHAOS AND COMPLEXITY IN THE MANUFACTURE OF ROMAN CONCRETE

The pozzolanic reaction with components of volcanic ash, water and quicklime is exothermic and introduces elements of Chaos and nonlinearity. This paper also attempts to present the reaction in terms of Chaos and Complexity and subsequent order.

The calcium clasts discovered by MIT researchers [7] and Jackson and colleagues are products of Chaos characterized by Complexity from the pozzolanic reaction leading to bifurcation and subsequent crystallization of the minerals Aluminous tobermorite and phillipsite, which retain the Complexity, furthering order, when the clasts dissolve , producing self healing of the concrete. The self healing patterns are ordered in multiple ways and can assume various geometrical designs. They spread through the concrete, thereby closing the cracks and even producing strength to the concrete, which is now durable.

VI. CONCLUSION

Roman concrete has lasted for more than two thousand years. Scientists have continued ongoing research on its durability and strength and many truths concerning the manufacture of Roman concrete have been revealed. Roman concrete differs markedly from modern concrete such as Portland cement in that it is stronger and more durable .While modern concrete cracks easily and the cracks spread , there is a self healing process in Roman concrete which covers the cracks and stops them from spreading . Thus the long durability of Roman concrete is justified.

The Romans made mortar by mixing volcanic ash , seawater and quicklime .The mortar was then mixed with the aggregate, which may have consisted of chunks of volcanic rocks to create concrete. This was a process performed more than two thousand years ago. After mixing , they would settle and gradually harden. The volcanic ash consists of both silica and alumina which proved crucial for a chemical reaction . When saltwater or seawater came into contact with ancient Roman concrete, it created a chemical reaction which was exothermic and produced enough heat. It was discovered that lime lumps or clasts were formed which, when dissolved , caused self- healing of any cracks in the concrete through a process of recrystallization with two minerals, aluminous tobermorite and phillipsite being formed.

The Roman concrete production involves a process which results in self healing[8] of the cracks , unlike modern or Portland cement, which has inert components .The durability of Roman concrete is attested in buildings such as the Parthenon and many sea structures made during Roman times , more than two thousand years ago.

This paper also proposes that the Pozzolanic reaction produces Chaos and bifurcation, causes Complexity in the form of lime clasts and results in order expressed in patterns of self-healing of the cracks , giving the ancient concrete durability for very long periods of time.

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