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Evolving Durability Strategies in Concrete Structures from the Roman Era to Today

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Abstract: Detailed Understanding of Roman concrete requires context from Roman military and civil engineering. The Romans prioritized durable infrastructure due to the impracticality of maintaining temporary wooden structures across their vast empire. This led to the development of long-lasting roads, bridges, and fortifications, many of which still exist today. Roman construction techniques, including concrete use, evolved significantly over time. Although Vitruvius documented early methods in the 1st century BC, later advancements—such as "hot mixing"—were not included in his texts. Roman concrete's durability, especially in late Empire formulations, contributed to its longevity and continued use through the medieval period. In modern times, concrete construction shifted towards heavily reinforced structures, often without adequate protection. This has led to durability issues, highlighted by events like the collapse of the Morandi Bridge. In contrast, Roman concrete demonstrates superior longevity and self-healing properties despite being unreinforced. The study of Roman concrete offers valuable insights for modern construction, suggesting that minimally reinforced or unreinforced methods inspired by Roman practices could enhance durability and sustainability.

Keywords: Concrete; Structures; Durability; Roman heritage; Reinforcement; Earthquake

1 Introduction

1.1 The Roman World

The Romans conquered much of the world through military force. Their military victories were based on the ability to strike quickly and decisively, tactically choosing when and where to act. Movement speed was critical, and victories were often achieved through foot marches and forceful engagement. Starting with the Battle of Veii (475 BC), the Romans fortified all their night camps, or "castrum." Over time, these fortifications were reinforced with stone materials. The Romans faced significant challenges with labor and energy resources. The steam engine, for example, would not be invented until much later. To understand the scale of this problem, let us consider a historical episode from Italy. In the 1930s, in Romagna (Italy), a recently reclaimed marshy land, groups of workers, known as "wheelbarrow brigades", would wake up in the middle of the night at the beginning of summer, typically in late March, to maintain the hydraulic works that kept the land free of water. This labor continued until late October. American engineers performed a remarkable feat after the Second World War, when the embankments remained unmaintained for over a year before the liberation (April 30, 1945). In front of entire villages, with a single excavator, they completed what would have taken the "wheelbarrows" many years of strenuous work in just over a week. This challenge of maintaining infrastructure in the absence of machinery was typical of the Roman world, where thousands of "castrum" fortifications were built across the empire. Every 30 to 36 kilometers along the Roman roads, there was a fortified camp where soldiers could rest for the night. This logistical system enabled fast and efficient movement of troops and supplies across the empire. To support this, the Romans had to construct durable fortifications that required minimal maintenance. As a result, the ruins of Roman military structures, which far outnumber the grand architectural works, are still scattered throughout the former empire. Roman construction techniques were continuously refined to meet these essential needs. Roman concrete, which originated around the third century BC, evolved significantly over time, continuing to develop until the construction of the second city walls of Constantinople in 410 AD. The Roman construction tradition, deeply embedded in the empire for military purposes, was rediscovered with Vitruvius' "De Architectura" [1] around the time of the Italian Renaissance. Recent coring of early medieval structures revealed the presence of highly abrasive aluminum and silicon compounds in the military walls, likely built around 700 AD. This suggests that Roman cement evolved over a millennium, and studying its development would be invaluable. Currently, we have two key references for Roman construction techniques: Vitruvius' descriptions from around 50 BC and a recent study of a sample taken from a military wall in "opus incertum" (likely constructed around 50 AD). Both sources describe similar types of Roman cement, with a significant difference in the "hot mixing" technique used in the 50 AD wall [2]. Roman concrete had two fundamental characteristics: limited energy requirements and minimal maintenance. The limited energy needs stemmed from the low maximum temperatures achievable with wood-fired ovens, even if resinous wood was used. The minimal need for maintenance was due to the protective properties of the opus used in Roman concrete construction, which could self-repair when cracked. Both Vitruvius and more recent studies confirm these characteristics. The type of "opus" used in a structure can provide an approximate dating of the artifact, as different types of Roman "opus" were employed during specific periods. For example, the "opus latericium", which was used in Roman buildings for a long time, can be identified by the size of the bricks, which evolved from the original "flat" brick to the current ISO brick size (250 x 115 x 60 mm). Roman bricks were typically categorized as "bessales" (197 x 197 mm), "sesquipedales" (444 x 444 mm), and "bipedales" (592 x 592 mm), with thicknesses growing over time from 35 to 70 mm. These bricks were often stamped, as brick manufacturing was a large-scale industrial activity. The brick production facilities (figlinae) were usually located near clay deposits and along river routes for easy transportation. Many of these facilities were likely owned by influential figures, often linked to the imperial family. Stamping bricks provided valuable information, and under the reign of Atalaric (516 - 534 AD), the last brick stamps, which were either circular or rectangular, were found.

1.2 The Development of concrete in Italy During the Autarky Era (1935-1940) and the Challenges of Unprotected Artifacts

In 1935, with the establishment of Autarky in Italy, the need to limit the use of steel in reinforced concrete became an official policy. This led to the development of construction techniques focused primarily on arches and tie rods, with limited use of reinforcing steel. These construction methods remained in use until the early 1970s. Initially, reinforced concrete structures were protected by plaster or stone coatings, but over time, they evolved into magnificent, uncoated concrete buildings. The widespread belief in the impermeability of modern pozzolanic cement further contributed to the misconception that concrete could adequately protect the steel reinforcement. As concrete gradually incorporated more steel reinforcement, the structures became stronger, but the introduction of anti-seismic regulations led to the extensive use of reinforcing steel. However, tragic events like the collapse of the Morandi Bridge in Genoa on August 14, 2018, highlighted the durability issues of uncoated reinforced concrete. The bridge, designed by Riccardo Morandi and inaugurated in 1967, later prompted Morandi to emphasize the need for a protective coating to safeguard the concrete. Steel reinforcement in concrete structures compromises their resistance to corrosion, as the formation of oxides leads to expansion, weakening the material. Additionally, the permeability of modern Portland-based cement makes unprotected concrete highly susceptible to deterioration and necessitates regular maintenance. This article argues for the need to protect modern reinforced concrete, develop less permeable concrete, and limit the use of reinforcement. Some Roman concrete structures, even without reinforcement, have withstood numerous earthquakes and remained durable. Similarly, specific autarkic-era structures exposed to significant seismic activity have also demonstrated resilience. This suggests that it is possible to create seismic-resistant reinforced concrete with limited reinforcement, which, while providing strength, is less prone to corrosion and deterioration.

2 Introduction to Roman Concrete

The Roman Empire (27 BC – 476 AD) was a period of exceptional architectural development, marked by continuous advancements in civil and military construction techniques. The ruins of Roman structures scattered across the Mediterranean are a testament to this remarkable engineering legacy. This section focuses on Roman concrete, an extensively studied subject, particularly its evolution from the first century BC to the fourth century AD. The first known descriptions of Roman concrete appear in the writings of Marcus Vitruvius Pollio (c. 80 BC – after 15 BC), whose famous treatise De Architectura was published in 1521 [1]. His work, translated into Italian by Caesar Cesariano, also inspired the founding of the Vitruvian Academy of Virtue in 1542. Strabo (60 BC – after 21 AD) wrote in his Geography about Roman infrastructure: "While the Greeks were renowned for choosing picturesque sites for their cities, the Romans demonstrated remarkable foresight in areas often overlooked by the Greeks, such as the construction of paved roads, aqueducts, and sewers that carried away city waste into the Tiber. Their roads were so wide that they could transport cargo as efficiently as a boat, and their aqueducts supplied such a large quantity of water that rivers flowed through the city, with fountains and cisterns in nearly every home." Initially, the Romans used mainly aerial lime as a binder for concrete. The hardening process was slow because it relied on the reaction between calcium hydroxide and carbon dioxide in the air, producing calcium carbonate. The term caementum referred to the material used in concrete, derived from the Latin word "caedo", meaning "to cut into pieces". This material was used to bind sand, crushed stone, and other aggregates, such as fragments of bricks and stones. However, Vitruvius' De Architectura [1] defined a more advanced form of concrete, opus caementicium, a key development in Roman construction. This technique involved creating walls by laying layers of overlapping mortar and inert materials. External facings made of bricks or squared stones served as permanent formwork, quickly filled with mortar and scrap materials such as stone or brick. In the third century BC, Roman concrete underwent a revolution by introducing pozzolanic ash (pulvis puteolana) or opus signinum, replacing some or all the sand in the mortar. This development significantly improved the concrete's strength, especially in underwater applications. In De Architectura [1], Vitruvius praises the pozzolanic ash from Baia and Cumae, noting its remarkable ability to strengthen construction materials, particularly in marine environments. This new concrete form is set and hardened even in water, without air exposure, making it a highly effective and durable material. The Romans' use of concrete in military construction, roads, foundations, and masonry from the first century BC to the fourth century AD laid the foundation for modern building techniques. Roman concrete, in its various forms, has stood the test of time, with many structures still standing today, showcasing the enduring legacy of Roman engineering.from the results.

2.1 Roman Concrete and Related Structures: Vitruvian Concrete

It is partially true that Roman ruins have survived through the centuries thanks to volcanic ash, contributing to the long-lasting durability of many Roman structures worldwide. However, this explanation alone does not account for the whole picture. Modern pozzolanic cement would offer the same remarkable longevity if it were as strong as Roman concrete. Yet, this is not the case. While modern pozzolanic concrete is more resistant to weathering than classic Portland cement, it still does not match the resilience of Roman concrete and lacks its self-repairing properties. The secret behind the exceptional strength of Roman concrete lies in the clever use of volcanic ash in the mixture and the meticulous preparation process. As Vitruvius wrote in "De Architectura" [1], "The pozzolanic ash of Baia or Cumae makes not only every kind of construction vigorous but particularly those built underwater." Thanks to the pozzolanic properties of this ash and "opus signinum" (a form of mortar), Roman concrete could set and harden even when submerged in water, without needing contact with air. This allowed the Romans to create high-strength binders resistant to environmental factors. Vitruvius further emphasizes the principles of Roman construction in "De Architectura" [1]: "All constructions must meet the criteria of robustness, utility, and beauty. Robustness will be ensured by digging the foundations until they rest on solid earth and choosing materials judiciously; utility comes from the careful arrangement of spaces and their functionality; beauty is produced through the pleasing and elegant appearance of the work, where the parts are proportioned harmoniously." Roman concrete, therefore, was made from lime, pozzolanic ash, and aggregate (stone), which revolutionized ancient building methods. It allowed the rapid construction of large public buildings and works using materials that were easily accessible, transportable, and simple to use. Basic mortar was composed of one part slaked lime to three parts sand, while hydraulic mortar—capable of setting underwater—was made with one part slaked lime to three parts pozzolana. The "caementa" (aggregate) was made from rough stones and broken rock fragments, such as tuff, travertine, flint, and pieces of bricks or tiles. Quicklime (calcium oxide) was obtained by heating limestone or marble in ventilated kilns at around 900 degrees C. When combined with water, quicklime turns into slaked lime, which can be stored as putty or lime flower, depending on its state. Slaked lime had natural disinfectant properties, preventing mold growth in lime-based plasters. The Romans used "opus signinum" to create waterproof mortar, a mixture of lime and pozzolanic ash further enhanced by adding crushed terracotta materials, such as bricks, tiles, and amphorae. This technique allowed them to construct foundations or core masonry, which was then covered by facings of bricks or stone. These facings were typically built in successive layers, with expert workers creating formwork to a specified height and laborers filling the gaps with the mortar mixture. Formwork could be made from bricks, tuff blocks, travertine, or marble. Clamps or iron brackets sometimes anchor the facings to the core. The holes seen in Roman concrete structures, such as the Colosseum, were drilled to remove the support brackets or to reclaim iron anchors. Some brick walls also feature regularly spaced holes that once held scaffolding during construction or restoration. Facings were often left exposed or plastered and decorated with frescoes, stuccoes, mosaics, glass pastes, and marble. Pozzolana is a volcanic ash created by eruptions and is found in varying grain sizes. The most famous quarries are in Pozzuoli, between Cuma and the Promontory of Minerva, from which the material gets its name. Its potential was recognized in the third century BC when it was first used to replace sand. The Romans later discovered its hydraulic properties when combined with lime, making it ideal for constructing bridges and underwater structures. To source the ash needed for cement, the Romans turned to deposits from the Alban Hills, which erupted about 456,000 years ago. The area contains three types of pozzolana: red, black, and pozzolanelles. Vitruvius describes the best pozzolana as "crunches, scratches, and makes a screeching sound when vigorously rubbed between the hands." The red volcanic ash used in the Trajan Markets is known for its characteristic "crackle" when rubbed. Vitruvius also provided insights into the best practices for mixing sand with lime in cementitious work. In "De Architectura" [1], he wrote: "In cement constructions, it is of primary importance that the sand is suitable for mixing with lime and not contaminated with earth. When rubbed in the hand, the sand that emits screech is considered the best." If suitable quarry sand was unavailable, river sand or sifted gravel could be used. Sea water could also be used, though it dries more slowly and may cause salt efflorescence, which deteriorates plaster. Pozzolana was not universally available across the Roman Empire, but many areas around Rome had rich deposits. These sites are often left behind complex tunnel systems, some of which are still used today for mushroom farming or are hidden beneath modern structures. The best pozzolana was red, while gray and black varieties were less effective. The discovery of pozzolana's hydraulic properties significantly improved the construction of vital infrastructure like ports and bridges. In "De Architectura" (V.XII) [1], Vitruvius explains the construction of foundations immersed in water using techniques remarkably like modern methods still in use today.

2.1.1 Flooded formwork (Foundations)

This technique involved constructing formwork as a dam, using oak planks secured by chains and transverse planks anchored to the bottom. The area inside the formwork was cleaned and leveled before being filled with a mortar made from two parts pozzolana, one part lime, water, and stones. Notably, the formwork remained submerged in water while the cement work was poured, allowing the mortar to set in these challenging conditions.

2.1.2 Precast blocks (Water foundations)

If the force of the waves or currents prevents the construction of a dam, a solid foundation is built at the edge of the mainland by creating a quay extending into the water. The quay is then enclosed by wooden embankments that remain above the water level and extend into the water. The space inside the embankments is filled with sand up to the water level. A concrete pylon is constructed on top of the sand base, as wide as possible, and allowed to dry for two months. After this period, the walls are removed, and the water gradually washes away the sand supporting the pylon, allowing it to settle onto the bottom. Repeating this process makes it possible to progressively extend dry land into the water.

2.1.3 Opus incertum

From 210 BC onwards, the "opus incertum" technique was used. This technique involved creating a cement structure whose surface is characterized by stones with irregular shapes and placements. In the second century BC, the aesthetic quality of this technique improved, evolving towards a more regular, almost reticulated pattern. The refinement of this technique can be seen in works like the Fortunati Sepulchre in the Via Latina tomb park. The two side retaining walls of these constructions were filled with Roman concrete.

2.1.4 Opus reticolatum

"Opus reticulatum", introduced in the early first century BC, was particularly prevalent and of high quality during the reign of Augustus. This technique involved creating a cement structure whose surface was covered with "tufelli"—blocks of tuff stone in a truncated pyramidal shape with a square base. These blocks were placed diagonally, with the truncated top facing outward, creating the distinctive "reticulated" pattern. The size of the blocks varied, typically measuring around 100 mm per side. The walls constructed with "opus reticulatum" could be left exposed or covered with plaster and decorated with stucco, marble, or other finishes. Interestingly, many "opus reticulatum" walls found today have been plastered, raising the question of why such intricate work was hidden. Perhaps plastering was a later fashion. Vitruvius, in "De Architectura," mentions that different types of walls—such as "opus reticulatum" and "opus incertum"—were commonly used in antiquity. While "opus reticulatum" was aesthetically superior, it tended to crack easily due to the instability of the joint beds. In contrast, "opus incertum" walls, made from stones laid randomly and cemented together, while less attractive, were more solid and durable.

2.1.5 Opus latericium

In "De Architectura," Book II [1], Vitruvius discusses the importance of brick production. Bricks were to be made in spring or autumn to dry at the correct pace, as drying too quickly would create a differential in moisture between the outer and inner parts of the brick, causing breakage. Furthermore, bricks must be aged for two years to prevent volume shrinkage. Vitruvius also described three types of bricks based on Hellenic architecture: "didoron" (2 palms long), "pentadoron" (5 palms long), and "tetradoron" (4 palms long), with each size having a corresponding half-length brick to create a staggered pattern for added strength. During the Roman Republic (3rd-1st century BC), large sun-dried bricks (known as "lidium") were commonly used for elevation structures; public architecture favored stone materials or cement-based walls.

2.2 The Imperial Concrete Structures

One of the most remarkable examples of Imperial Roman concrete is the complex of Trajan's Market, constructed around 113 AD by the architect Apollodorus of Damascus. This structure, which features a semicircular arrangement of halls on three levels, has withstood three significant earthquakes (443 AD, 1349, and 1703) and remains an enduring testament to Roman engineering prowess.

2.2.1 Opus mixtum (Figure 1)

At the beginning of the Augustan era, using bricks led to the evolution of "opus mixtum", which combined horizontal bands of bricks with sections of "opus reticulatum". This hybrid technique strengthened the structure and helped address the oblique cracks in the reticulated walls, as seen in the Villa delle Vignacce in the Parco degli Acquedotti. This technique was further refined during the Flavian period using lateral brick supports. One notable example of "opus mixtum" is the city walls of Constantinople.

Figure 1. Walls of constantinople

(By Antonio cali 66 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=83859035)

2.2.2 Brickwork (Opus testaceum and opus latericium)

Brickwork was widely used throughout the Imperial period, consisting of both sun-dried bricks ("opus latericium") and kiln-fired bricks ("opus testaceum"). The term "brickwork" generally refers to both types.

(1) Opus latericium (Sun-dried bricks)

While sun-dried bricks were cheaper, they were more vulnerable to weathering and could be reinforced with straw or other fibers. They could also be shaped into triangular forms to improve grip in "opus cementitious" walls, where the cement was poured between rows of bricks. Over time, some buildings, like the Trajan Markets, began showcasing exposed brickwork, while others used decorative stucco or marble finishes.

(2) Opus testaceum (Kiln-fired bricks)

Kiln-fired bricks, or "opus testaceum," were more durable and resistant to the elements but more expensive. The use of fired bricks in Roman construction came later than stone, primarily focusing on terracotta roofing and tiles until the first century BC. Fired bricks were later incorporated into masonry, initially for decorative purposes in roofing and floors. Roman bricks were standardized by size, typically measured using the Roman foot (296 mm). The most common sizes included "bipedales" (2 Roman feet), "sesquipedales" (1.5 Roman feet), and "bessales" (2/3 Roman feet), with thicknesses ranging from 35 to 70 mm. Bricks were often cut into triangular shapes for formwork in "opus testaceum" walls, with whole bricks placed intermittently for structural stability. The construction of "opus testaceum" masonry involved creating two parallel brick curtains, with triangular bricks placed between them and cement poured to bind the structure. Larger bricks were used intermittently to distribute loads and reduce lateral pressure on the walls. This technique became widespread in imperial architecture, although the brickwork was often concealed under plaster, stucco, or marble. One of the most iconic examples of "opus testaceum" is the Pantheon, which features exposed brickwork in its massive, vaulted dome. The innovative use of lighter materials in the upper areas of the dome allowed the Romans to achieve an unprecedented 43-meter-wide space. The Pantheon remains one of the best-preserved Roman structures, showcasing the technical and aesthetic achievements of "opus testaceum".

2.2.3 Listed work (Opus vittatum)

The opus vittatum emerged toward the end of the second century AD. It is characterized by walls constructed with concrete covered in alternating layers of parallelepiped tuff blocks (tufelli) and brick courses. A notable example of this technique is the four-sided portico of the Mausoleum of Romulus (4^{th} century AD) along the Appian Way. In some variations, tufelli could be replaced with fired clay blocks, and the alternation between brick and tuff could be a single row of bricks followed by a single row of tufelli. Lateral brick joints were also integrated at corners, doors, and windows, such as in the Villa dei Sette Bassi (mid-second century AD, Aqueduct Park) walls.

2.3 Mechanical Properties of the Roman Concrete

X-ray analysis of a sample from Trajan's Market (100-112 AD) revealed that the Roman mortar contained stratlingite, a mineral known for enhancing the durability of modern cementitious mixtures. Stratlingite (C_2ASH_8) is stable at ambient temperatures, closely related to hydro garnet minerals like hydrogrossular, kotoite, and others, improving cement properties. A study on Roman cement used in harbor construction, which still endures aggressive marine conditions, uncovered that the Romans' blend of volcanic ash (or rock) and lime created a remarkably resilient material that was difficult to match with modern cement. This mixture facilitated the growth of interlocking minerals when exposed to seawater, making the concrete highly resistant and strong. In his Naturalis Historia (79 AD), Pliny the Elder noted that Roman concrete structures in harbors "became a single mass of stone impenetrable to the waves and stronger every day" despite constant exposure to seawater. Modern research confirms Pliny's observations. The interaction between seawater, volcanic ash, and lime in Roman concrete encourages the formation of durable crystalline structures within the mixture. This pozzolanic reaction, named after the town of Pozzuoli in the Bay of Naples, occurs when ash, water, and lime mix, forming crystals that fill gaps and strengthen the material. This process mimics natural occurrences, such as the formation of "tuff", a naturally occurring cement-like material found in volcanic regions, which likely inspired the Romans. Further studies, such as those on the Roman pillar at Portus Cosanus in Orbetello, Italy, using high-powered X-ray analysis, showed that minerals continued to grow in the cracks caused by tidal erosion. This ongoing mineral growth reinforced the concrete over time. One of the more surprising findings is the role of lime clasts (small lime particles) in Roman concrete [2]. Initially thought to be a by-product of poor mixing, recent studies have shown that lime clasts were intentionally included to improve concrete durability. The lime clasts reacted with water that seeped into cracks, recrystallizing and filling gaps, effectively "healing" the concrete. This healing process allows concrete to maintain its integrity over centuries. Experiments with hot mixing to produce lime clasts demonstrated that cracks could be fully sealed in as little as two weeks when exposed to water. Additional research by Masic in 2021 [2] confirmed the remarkable durability of Roman concrete, noting the unusual chemical interactions between volcanic ash and rainwater over the past two millennia. These interactions contributed to the cohesion and strength of the concrete, further proving the advanced engineering techniques employed by the Romans in their construction materials.

2.3.1 Discussion on Roman concrete

The studies referenced [2, 3] focus on Roman concrete, revealing significant variations in its use and composition based on the specific construction needs. Vitruvius highlighted the diverse applications of concrete, noting how its use differed for vertical walls, floors, domes, and foundations, depending on whether they were built on land or in water. As mentioned in the introduction, concrete development followed a gradual progression, much like the evolution of other building materials such as bricks. For example, Prof. Asic of MIT conducted research on the concrete used in the Tomb of Cecilia Metella (1^{st} century BCE) [3] and the military walls of Privernum, Italy (50 AD) [2]. His study of the military walls led him to identify the use of "hot mixing" in their construction [2], a technique not previously recognized. The use of concrete differed significantly between military and civilian applications, influenced by available resources, funds, and specific requirements. As a result, the findings from research on Roman concrete are often inconsistent, particularly regarding its mechanical properties. The variation in techniques and materials used for different types of construction makes it challenging to draw definitive conclusions about the concrete's overall performance.

2.3.2 Notes on the chemical composition of Roman cement

The Ancient Romans used a slaking process to create their first mortar, which was composed of lime. Before application, they would mix the pozzolan and hydrated lime on-site. This process helps explain the small amounts of CaO in Table 1, as the lime (CaO) was added later to the mixture. In contrast, modern Portland cement involves incorporating lime (CaO) through kiln sintering, producing a powder-like cement that is then hydrated with water on-site before application. A key distinction between ancient and modern cement processes lies in the sintering of contemporary cement. Modern cement sintering likely involves a ferrite phase, which enhances ion mobility and accelerates the kiln's fusing process. This contrasts Roman concrete, where such a ferrite phase was less significant. Furthermore, Roman concrete's high alumina and silica content explains why it causes more wear on cutting tools than present-day Portland cement. In 2008, Hohlfelder et al. [4] constructed a full-scale Roman-style formwork in the harbor of Brindisi, Italy, using the same materials and formulas recommended by Vitruvius. They built an 8 m^3 hydraulic concrete block for the project. Cores from this newly constructed concrete were analyzed visually, chemically, and through engineering methods. These results were compared with a 6-meter-long core extracted from the Villa of the Domitii Ahenobarbi at Santa Liberata, which is likely dated to the first century BC. The analysis provided the first insights into the curing process of Roman concrete. Table 2 summarizes a few results from these works [4, 5].

Table 1. Ancient pozzolan-based Roman cement (Vitruvius recipe) vs. Portland cement.

	SiO_2 Silica Silicon Dioxide	Al_2O_3 Alumina Aluminum Oxide	Fe_2O_3 Rust Iron Oxide	CaO Lime Calcium Oxide	Ignition Loss	Other
Roman	55.8	19.2	4.0	3.6	4.6	12.8
Portland	21.5	5.2	2.8	66.6	0.8	3.1

Table 2. Roman concrete and Portland mechanical properties [4, 5]

Site/age	Elastic Modulus E [MPa]	Compressive Strength R [kPa]	Density ro [$\mathrm{kg\ m^{-3}}$]	E/ro	R/ro
Cosa (98-117) [5]	18800	9400	2163	8.7	4.3
Portus (41-54) [5]	5560	6300	1583	3.5	3.9
Average of concrete the study [5]	7761	6745	1650	4.7	4
Vitruvius (2005) [4]	3800	3700	1400	2.7	2.6
Ex Vitruvius with 2.7:1 Pozzolana/Lime (2005) [4]	5750	7200	1530	3.8	4.7
Santa Liberata (50 BC?) [3]	6420	8000	1533	4.1	5.2
Portland	24800	27600	2325	10.7	11.9

As shown in Table 2, Roman cement from the late period likely exhibits better mechanical characteristics, although these concretes were primarily used for foundations or ports. The "hot mixing" article references concrete used in walls [2]. Roman concrete, like modern construction materials, had many variations depending on its intended use, available resources, and economic considerations. Unlike brick, which was mass-produced, Roman concrete was mixed on-site and tailored to specific needs. Just as in modern construction, there were different types of concrete for various purposes such as foundations, civil walls, military walls, and domes. Roman concrete recipes were refined and adjusted to optimize their performance as knowledge advanced. It would be valuable to analyze samples from structures of known periods and use, such as the two walls of Constantinople, which were built with considerable resources. With sufficient sampling, both for statistical analysis and material types, it would be possible to assess the actual performance of Roman concrete and its potential for industrial production. Vitruvius' recipe, as indicated [4], offers general guidelines regarding materials and proportions but is likely outdated, as evidenced by more recent findings [3]. Roman cement may have persisted, at least in some forms (recipes), until the tenth century (as seen in the Castello di Mordano in Bologna, Italy), with its high abrasiveness attributed to replacing lime with silica and increased alumina content.

3 The "Rebirth" of Concrete

Figure 2. Construction of the Eugenio Miozzi's Liberty Bridge – Venetian Lagoon - Italy (1931)

Figure 3. Faculty of Engineering of Bologna, designed by Giuseppe Vaccaro (1896-1970). It was built between 1931 and 1935 on the first hills above Bologna – Italy

The humanistic revival, particularly after the 14th century, led to the translation and re-examination of Latin texts by Pliny the Elder and Vitruvius, reviving knowledge of Roman concrete techniques. In 1511, Giovanni Monsignori (Fra' Giocondo) re-edited De Architectura [1], contributing to the gradual rediscovery of concrete construction, especially in 18th-century France. British engineer John Smeaton discovered hydraulic lime while constructing the Eddystone lighthouse, marking a key step from Roman concrete to modern cement. Smeaton's discovery and the emerging chemical sciences laid the foundation for developing modern Portland cement. The transition from Roman to modern cement accelerated in the late 18th and early 19th centuries, particularly in England and France. In 1796, Parker developed Roman cement by firing Thames clay in lime kilns, and in 1800, Lesage produced high-strength hydraulic material. The turning point for modern cement came in 1818 when Vicat defined the formula for artificial hydraulic lime. In 1824, Joseph Aspidin of York created the first industrial Portland cement, which was later refined with high-temperature firing methods in the 19th century. M. Chatelier's work in 1860 established the chemical composition of cement, enabling the industrial production of concrete. The widespread use of concrete expanded with the advent of reinforced concrete, which combined cement with steel to provide better tensile strength. While ideas for using steel in concrete structures emerged in the 17th and 18th centuries, it was in the 19th century, especially with the Industrial Revolution, that reinforced concrete became widely used. In 1847, Coignet designed the first concrete roof reinforced with iron, and Lambot created a boat with a concrete hull. The invention of reinforced concrete is credited to Joseph Monier, who patented his system in 1877. This system became popular in Europe, and in 1886, Koenen published the first theoretical and experimental analysis of reinforced concrete. François Hennebique patented his reinforced concrete system in 1892, incorporating key innovations like U-shaped flat bars for stirrups. Hennebique's system, combined with his business success, solidified the widespread use of reinforced concrete, and by 1896, he founded Le Beton Armé, further promoting the development of the field. Following issues with buildings constructed for the Exposition Universelle of 1900, the Reinforced Concrete Commission established the Ministerial Circular of 20 October 1906, which removed control of concrete from patent holders, allowing it to be freely used by entrepreneurs. This led to significant advancements in concrete quality, transitioning from "dosage concrete", where specific quantities of materials were prescribed to achieve a particular strength, to "resistance concrete", where only the strength class (Rck) was specified. More recently, the focus has shifted to "performance concrete", which ensures strength, durability, and workability, with detailed specifications for strength class, exposure, consistency, and aggregate size. This evolution reflects a shift from site-mixed concrete, where workers manually followed design proportions, to ready-mix concrete produced in industrial batching plants. These plants ensure precise mixing and quality control, delivering high-tech concrete that meets the required classes. The quality of concrete has further improved with the addition of supplementary materials and additives, enhancing the performance and behavior of concrete mixtures. During the debate in Italy in the second half of the 1930s, one of the most discussed issues was the limitation of iron usage in construction and concrete structures due to its significant architectural, technical, and economic implications. In structural terms, this led to efforts to find practical ways to reduce iron consumption and clarify the uncertainties surrounding the behavior of reinforced concrete to establish a foundation for classical theory. The question of iron also prompted advancements in material and construction technology, yielding some of the most noteworthy results in the post-war period, influencing a distinctive Italian approach to design and construction. In Italy, a few years after the Scythe Competition (1931-32), which took place at a particularly favorable time for steel due to the collapse of raw material prices on global markets, the steel structure, which had already struggled to gain widespread use, was further overshadowed by the economic and political situation following the League of Nations sanctions in November 1935. Iron, largely reliant on imported raw materials, was not autarkic, reinforcing the validity of research into lightly reinforced concrete. This line of inquiry, which had begun earlier with a competition organized by the Fascist Industrial Federation of Concrete at the end of 1935, led to the development of widely used construction techniques, such as arched bridges, like the Liberty Bridge (Figure 2), and continuous casting concrete structures, such as the Faculty of Engineering in Bologna (Figure 3).

Both examples feature concrete structures protected by plaster and bricks. However, there are more audacious examples, such as the Massawa Bridge (Figure 4), which was built with unprotected reinforced concrete, like the Morandi Bridge in Genoa (Figure 5). These structures share a common characteristic: the minimal use of reinforcing steel, reflecting the principles of the "Italian school". While protected structures withstand the elements and time with little issue, "bare" reinforced concrete structures require ongoing maintenance. Modern cement, even the so-called "Pozzolanic" variety, lacks the same level of protection, unlike the concrete used by the Romans, which demonstrated superior durability.

Figure 4. Massawa Bridge (1938) with the characteristic hinge in the arc to reduce thermal stress

Figure 5. Bridge designed by Riccardo Morandi (1902 -1989) (Polcevera – Genoa - Italy - viaduct A10 - 1967)

4 Considerations on the Durability of Structures and Concrete Resistance to Earthquakes

In the mid-twentieth century, concrete structures were typically designed with an expected service life of approximately 50 years, and many were even regarded as temporary. However, the standard has shifted significantly, and modern buildings are often designed to last 100 to 120 years. Adopting a mindset like that of Roman engineers could benefit long-term infrastructure such as bridges, roads, and aqueducts. Their approach emphasized durability through practical, long-lasting construction solutions. One of the most essential lessons from Roman engineering is that structures should be designed for endurance and longevity. As discussed in the section on Roman concrete, the remarkable self-healing capability of Roman structures was a key contributor to their long-term durability. In addition to material performance, external protective features, such as stone cladding and corrosion-resistant roofing, played a vital role in preserving Roman concrete, allowing many structures to survive for centuries with minimal maintenance. Concerning earthquake resistance, it is noteworthy that many Roman structures exhibited a capacity for gradual self-repair despite experiencing fractures during seismic events. This underscores the value of integrating "crack stoppers" into structural design—features that intentionally interrupt the propagation of cracks. In Roman construction techniques such as "opus mixtum", this was often achieved by introducing barriers within wall coatings or mortar layers. Another essential principle for seismic resilience involves reducing the mass of upper structural components. This can be accomplished through lightweight aggregates or specialized concrete mixtures, as exemplified by the construction of the Pantheon dome. Reducing the weight of higher elements minimizes inertial forces during seismic activity and enhances overall stability. Proper structural design must also account for the complex displacements caused by earthquakes, which typically include both vertical and horizontal movements. In a simplified model, a vertical structure subjected to seismic forces can be approximated as a cantilever beam fixed at its base and loaded by its mass. For analytical purposes, consider a vertical cantilever beam of height H [m] and total mass M [kg], assumed to be uniformly distributed along its height. The building's mass per unit length, m, can be expressed as (1):

$$m = \frac{M}{H} \tag{1}$$

During an earthquake, the instantaneous ground acceleration vector can be decomposed into horizontal a_h [m s^{-2}] and vertical a_v [m s^{-2}] components, which generate dynamic inertial forces throughout the structure. These forces must be resisted by a combination of structural geometry, appropriate material selection, and strategic detailing to ensure long-term performance. The distributed horizontal load would be w [N m^{-1}] (2):

$$w = m\, a_h \tag{2}$$

The horizontal component of seismic acceleration causes the structure to behave like a cantilever beam subjected to a uniformly distributed lateral load. This results in bending, with the maximum deflection occurring at the structure's top, as Eq. (3) describes. The ultimate deflection, denoted as fultimate [m], corresponds to the point at which the material reaches its maximum allowable deformation before cracking occurs. Therefore, we have (3):

$$f_{ultimate} = \frac{w\, H^4}{8\, E\, J} \tag{3}$$

E [Pa] is the elastic modulus of the homogenous material, and J [m^4] is the Inertia modulus. From Eq. (3), maximum M_{max} [N m] is equal to (4):

$$M_{\max} = \frac{wH^2}{2} = \frac{4\, E\, f_{ultimate}\, J}{H^2} \tag{4}$$

In the case of earthquakes, concrete with a smaller elastic modulus E performs better than more rigid alternatives, as it can absorb and dissipate seismic forces more effectively. As shown in Table 2, Roman concrete appears to have a lower elastic modulus, likely enhancing the earthquake resistance of structures built with it. Flexural stress also plays a critical role in the presence of vertical acceleration, as it can lead to beam instability and contribute to reaching the critical buckling load. It is essential to recognize that traditional techniques, such as structural hooping, are effective under static loading conditions [6, 7]. However, during seismic events, these hoops can act as discontinuities within the structure, promoting crack initiation and propagation, ultimately increasing the risk of structural collapse. Moreover, in structural analysis, it is essential to note that the instantaneous acceleration vector cannot be decomposed into independent vertical and horizontal components when dealing with nonlinear behavior. In such cases, the principle of superposition no longer applies, and the interaction between components must be considered part of a coupled, nonlinear dynamic response.

5 Discussion

Modern concrete structures are now expected to last 100–120 years, in contrast to older estimates of 50 years. On the contrary, the Romans prioritized long-term durability, using materials and techniques that allowed structures to self-heal and withstand earthquakes. Key takeaways from their approach: lightweight upper elements, like in the Pantheon, reduce seismic forces. Crack stoppers in Roman walls helped control the damage. The lower elastic modulus of Roman concrete enhanced its ability to absorb seismic energy. Romans protected concrete with walls and other containment structures. They did not use steel reinforcements.

6 Conclusions

Studies of Roman concrete from the imperial era show that it is very durable, resistant to aging and harsh environments, and can self-repair. This durability is evident in how these structures have withstood the effects of time and earthquakes. The low elastic modulus of Roman concrete likely played a role in this resilience. The Romans often covered their concrete with "OPUS" in various materials, including "crack stoppers". Like Roman methods, post-war Italian concrete structures have demonstrated that building earthquake-resistant structures with minimal steel reinforcement is possible. Steel can rust and expand when not adequately protected, causing the concrete to crack and deteriorate. Today, we design buildings to last for over a century, but we could benefit from thinking about building structures that last for millennia as the Romans did. Using concrete, protecting it with coatings, and minimizing steel reinforcement could help us achieve this long-term durability.

Author Contributions

Conceptualization, E.L.; investigation, L.P.; writing—original draft preparation, L.P.; supervision, E.L. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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