Precision Mechanics & Digital Fabrication
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Reassessing Roman Structural Longevity: From Firmitas to Eurocode Through the Lens of Modern Cementitious Technologies

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Received: 05-10-2025 **Revised:** 06-26-2025 **Accepted:** 07-03-2025

Citation: L. Piancastelli and E. Lorenzini, "Reassessing roman structural longevity: From firmitas to eurocode through the lens of modern cementitious technologies," *Precis. Mech. Digit. Fabr.*, vol. 2, no. 3, pp. 134–145, 2025. https://doi.org/10.56578/pmdf020301.

Abstract: The enduring resilience of Roman infrastructure, exemplified by the Tiberius Bridge in Rimini—completed in the 1st century CE and remaining structurally sound after over two millennia—has long drawn scholarly attention. This study re-evaluates Roman construction methodologies with a particular focus on *opus caementicium* (Roman concrete) encased within durable permanent facings such as *opus quadratum*, *opus incertum*, and *opus latericium*. Central to this longevity was the use of pozzolanic binders, which underwent prolonged hydration reactions, enabling continued strength development over extended timescales—markedly contrasting with contemporary hydraulic cements engineered for rapid early-age strength gain. A comparative analysis is conducted between ancient Roman materials and modern high-performance cementitious composites, including High-Performance Concrete (HPC), Ultra-High Performance Concrete (UHPC), and Engineered Cementitious Composites (ECC). Contemporary practices are frequently guided by design codes such as Eurocode, which, while structurally robust, tend to prioritize short-term performance metrics. To bridge this gap, a hybrid construction strategy is proposed wherein additive manufacturing is employed to produce permanent structural formworks that mimic the load-bearing and protective functions of Roman facings. This approach enables the use of modern slow-maturing binders within digitally fabricated enclosures, thus integrating ancient durability principles into automated, scalable workflows. By reconciling historical construction insights with advances in modern materials science and digital fabrication, a new paradigm is introduced for designing infrastructure with service lives far exceeding the conventional 50–100 year design horizon. The implications of such an approach extend to both sustainability and resilience, offering a technically viable and historically informed route toward ultra-durable infrastructure in the face of evolving environmental and operational challenges.

Keywords: Roman concrete; Pozzolanic reaction; Engineered Cementitious Composites (ECC); Modern cement technologies; Additive manufacturing; Permanent formwork; Durability

1 Introduction

Durability was a foundational principle in Roman engineering. As Vitruvius emphasized in *De Architectura*, architecture must embody three essential qualities: *firmitas* (strength), *utilitas* (functionality), and *venustas* (beauty) [1]. Roman builders operated in a context where maintenance was impractical due to the absence of mechanization and the reliance on manual labor. As a result, structures were designed with extraordinary robustness and longevity in mind.

The legacy of Roman engineering is visible in structures such as the Pont du Gard aqueduct in France, the Alcantara Bridge in Spain, and the Pantheon in Rome, whose unreinforced concrete dome remains the largest in the world [2, 3]. The Cloaca Maxima, a massive sewage infrastructure, was used continuously from the 6th century BCE until the early 21st century [4]. These examples illustrate a construction philosophy focused on permanence rather than convenience or initial cost minimization.

In contrast, contemporary structures—particularly those built in the second half of the 20th century—often suffer from premature deterioration. Common issues include reinforcement corrosion due to chloride ingress, carbonation of concrete, alkali-silica reaction, freeze-thaw damage, and poor detailing practices [5, 6]. Many post-war concrete structures built with minimal cover and low-quality materials are now in critical need of repair or demolition, despite being only a few decades old.

This observation raises a critical issue regarding long-term economic viability: how cost-effective Roman structures were if, after nearly two millennia, many continue to serve their intended function while numerous modern constructions experience functional obsolescence within only 50 to 100 years.

This paper explores the possibility of designing ultra-durable structures using modern materials available on the commercial market. In particular, it examines the role of stainless-steel reinforcements, which exhibit significantly higher resistance to corrosion in aggressive environments [7]. Other promising technologies include HPC, UHPC, and fiber-reinforced polymers (FRP), which offer improvements in durability and mechanical performance [8–10].

Design strategies are reviewed within the framework of current standards such as Eurocode 2 [11], ISO 16204 [12], and ASTM C1202 [13], emphasizing durability as a performance criterion rather than an afterthought. By combining ancient design wisdom with advanced modern materials and engineering knowledge, this study aims to identify pathways toward constructing infrastructure with service lives measured in centuries rather than decades.

2 The Bridge of Tiberius: History and Wartime Events

The Bridge of Tiberius, more accurately known as the Bridge of Augustus and Tiberius, is a Roman bridge located in Rimini, Italy. Its construction began in 14 AD under Emperor Augustus and was completed in 21 AD during the reign of Emperor Tiberius. Since 1885, it has been recognized as a national monument. The bridge is depicted on the coat of arms of the city of Rimini and marks the initial section of the ancient Via Emilia. It is situated to the northwest of the historic city center, connecting two of Rimini's oldest districts.

An imitation of the Bridge of Tiberius exists in Ireland. While not as aesthetically refined due to its narrower piers—based on a design by Palladio—this replica features five elliptical arches spanning the River Nore (in Irish, *An Fheoir*), in contrast to the semicircular arches of the original. The building material differs as well: instead of Istrian white stone, the Irish bridge employs the local blue limestone of Kilkenny. Although the original Roman bridge remains in good condition, its Irish counterpart—celebrating its 250th anniversary this year—requires restoration; notably, its deteriorated northern parapet was replaced with a steel railing in 1969.

Remarkably, the Bridge of Tiberius has withstood earthquakes and various wartime threats. Notable events include seismic shocks in 1672 and 1786, an attempted destruction during the Gothic War in June 552 AD, an alleged arson attempt by Pandolfo Malatesta in 1528, and near-demolition during the Second World War. To this day, it serves as a key pedestrian crossing for those entering the historic center from the lively fishermen's quarter of San Giuliano.

Locally, the structure is known as the "Devil's Bridge", a moniker earned not only for its longevity and seeming invulnerability but also due to a specific wartime incident during World War II. According to German military doctrine, all infrastructure was to be destroyed during retreat to prevent enemy use. This included the remaining major monuments in Rimini: the Arch of Augustus and the Bridge of Augustus and Tiberius. On 20 September 1944, Field Marshal Albert Kesselring ordered the demolition of such structures to slow the Allied advance, with Canadian forces having broken through at Covignano and threatening the city's encirclement. Engineer Willi Trageser of the First Parachute Pioneer Battalion was tasked with the demolition. Assessing the Arch of Augustus, Trageser decided against its destruction, reasoning that its isolated position rendered the operation futile. He later stated: "I personally ordered that the arch not be blown up, assuming full responsibility. It seemed absurd to destroy such a historic monument for no practical gain."

The bridge, however, presented a more strategic target. That night, Trageser's team installed approximately 100 kg of ammonal at the base and another 160 kg distributed in eight boreholes drilled under the roadway and connected via gutter piping. Despite the careful placement, the detonation resulted only in noise and smoke, causing negligible damage. Trageser later explained: "There was a tangle of wires, resulting in only a partial explosion. The use of gutters turned out to be the bridge's salvation: the detonators malfunctioned, and only two charges ignited." The damp weather likely further compromised the effectiveness of the ammonal, which is known to absorb moisture.

Trageser made two more unsuccessful attempts. With Allied troops approaching in the early hours of 21 September, he falsely reported the bridge as destroyed—possibly to avoid capture. The next morning, the structure was found fully intact and unobstructed by Allied forces, who used it immediately. Ironically, some escaped German prisoners, returning from Ancona in a stolen truck, confirmed its functionality by re-crossing it.

This deception placed Trageser in a precarious position. He claimed in his defense that, observing a tall column of smoke, he had assumed successful demolition without verifying due to poor visibility and the urgency of retreat. Fortunately for him, German command accepted his explanation and took no further action.

Unbeknownst to all, undetonated explosives remained embedded in the bridge. For more than a decade, thousands of vehicles—including heavy military convoys—crossed the bridge, unaware of the lingering threat. It was only on 29 January 1957 that a maintenance worker discovered the unexploded charges, bringing an end to one of the most curious wartime episodes surrounding this ancient Roman structure. The Tiberius Bridge remained in service for vehicular traffic until the early 2000s, withstanding over the years even medium-sized trucks without exhibiting structural distress. According to local oral history, in the days following the liberation of Rimini on September 21, 1943, American Sherman tanks are said to have crossed the bridge. Although no official documentation confirms this daring passage, the bridge has nonetheless proven to be extremely robust and remarkably low-maintenance. Its long-standing functionality underscores the durability and efficiency of Roman engineering in both structural performance and lifecycle economy (see Figure 1).

Figure 1. Tiberius Bridge in Rimini, Italy. By Sailko, lic. Creative Common (CC BY-SA 3.0)

3 Notes on Roman Concrete—*Opus Cementicium*

The Roman concrete documented by Vitruvius [1] remains a mysterious and partially misunderstood material. Some archaeologists have extracted historical samples and subjected them to modern mechanical testing, while others have attempted to reproduce the material experimentally. These studies revealed discrepancies between Vitruvius's recipe and actual ancient formulations, particularly with the introduction of a method now referred to as hot mixing. The recipe provided by Vitruvius has proven to be rather approximate, often yielding concrete with modest mechanical properties when compared to some high-performance ancient specimens.

The issue is complex, as Roman concrete—like Roman architecture in general—was governed by a hierarchy of cost, quality, and functional priority. The highest quality and most expensive concretes belonged to what may be termed *military concrete*. This category included fortifications, bridges, harbors, and essential infrastructural works such as aqueducts, dams, and cisterns. In the absence of sufficient resources, even military constructions were sometimes made of timber, typically oak or chestnut. Remarkably, some of these wooden structures, owing to their excellent craftsmanship, have survived to the present day—such as the bell tower of Villemaur-sur-Vanne (Aube, France).

Thus, concrete constructions were reserved for when it was truly justified—and when they were built, they were built well. Public works followed in this hierarchy. The finest examples of Roman concrete are often found in Imperial Rome, where renowned architects risked not only their reputations and profits but, in some cases, even their lives. Below this tier were patrician houses, which were often subject to speculative building practices; in some cases, builders economized by reducing the quality of materials used. Finally, there were funerary structures, whose quality varied greatly depending on the context and resources available.

Producing high-quality Roman concrete required transporting selected raw materials, a reliable labor force, and significant quantities of consumables. Cement production in particular demanded the use of resinous wood for burning. Nevertheless, the cement had to be of sufficiently high quality to justify its use over standard bricks, which were themselves mass-produced under controlled processes. Roman bricks, often fired using thermal control tools such as temperature cones, were of excellent quality. Therefore, only cement with superior performance characteristics was economically viable. It is no coincidence that the Byzantines, in contrast, built most of their structures—including Hagia Sophia—almost entirely with bricks, reserving concrete primarily for military walls.

The situation is further complicated by the existence of multiple types of Roman cement, each with distinct properties. Some formulations were weaker but more resistant to corrosion, making them suitable for maritime structures. Others were optimized for walls and fortifications, while intermediate mixes were used for general structural applications. For instance, the Theodosian Walls of Constantinople were built using military-grade concrete.

Finally, Roman cement technology evolved significantly over time, with continual improvements at least until the fourth century AD. Properly characterizing this material today would require the fabrication of high-quality test specimens suitable for statistically meaningful destructive testing. As such, our current understanding of Roman concrete remains far from complete. The values and assumptions presented in this work should therefore be regarded as broadly approximate.

4 Structural Analysis of the Tiberius Bridge Arch in *Opus Caementicium*

The load-bearing capacity of a highway bridge, expressed in $\mathrm{kN/m^2}$, varies depending on applicable regulations and specific design requirements. This capacity is influenced by several key factors.

One of the primary considerations is the variable load, which accounts for the weight of vehicles such as trucks, cars, and other forms of transportation that travel across the bridge. Design standards specify reference values for these loads to ensure structural safety under normal traffic conditions.

In addition to distributed loads, the design must also account for concentrated loads, particularly those generated by the axles of heavy vehicles. These loads act at discrete points on the bridge deck and must be considered in structural analyses to assess localized effects and verify the strength of critical components.

Another significant factor is the permanent load, which includes the self-weight of the structure. This encompasses all structural elements such as the deck slab, main beams, parapets, and safety barriers. The permanent load is a constant acting on the structure throughout its lifespan and must be included in the overall load combination used for design.

Finally, the load-bearing capacity is determined in accordance with relevant technical standards. In Italy, for example, the Italian Technical Standards for Construction (Norme Tecniche per le Costruzioni, NTC) define the criteria, load models, and safety factors to be applied in the structural verification of bridges.

In summary, the load capacity of a highway bridge is a complex parameter influenced by several factors, including variable loads, concentrated loads, permanent loads, and applicable regulations. While specific values may differ depending on the context, a standard design value commonly adopted is 95 $\mathrm{kN/m^2}$.

The bridge under consideration extends over a length of approximately 74 meters and has a total width of approximately 8.8 meters. Originally, the carriageway measured approximately 4.7 meters and was flanked by sidewalks intended for pedestrian use. Assuming the pedestrian load is negligible, the equivalent distributed load acting on the bridge is calculated as:

$$q = \frac{95 \cdot 4.7}{8.8} = 48 \mathrm{kN/m^2} \tag{1}$$

The following analysis concerns a semicircular Tiberius Bridge arch constructed in *opus caementicium*, subjected 141 to a uniformly distributed vertical load. The arch has a clear span of 8.80 m and a thickness (in the longitudinal direction) of 2.42 m. The total width of the structure is assumed to be 8.80 m as well (see Figure 2).

The radius of the arch is computed as:

$$R = \frac{L}{2} = \frac{8.80}{2} = 4.40 \mathrm{~m} \tag{2}$$

Assuming a uniform vertical load of 48 $\mathrm{kN/m^2}$ over the entire surface, the equivalent line load becomes:

$$q = 48 \frac{\mathrm{kN}}{\mathrm{m^2}} \times 8.80 \mathrm{~m} = 422.4 \frac{\mathrm{kN}}{\mathrm{m}} \tag{3}$$

The self-weight of the *opus caementicium* is also considered, with a density of 2000 $\mathrm{kg/m^3}$, corresponding to a specific weight:

$$\gamma = 2000 \frac{\mathrm{kg}}{\mathrm{m^3}} \times 9.81 \frac{\mathrm{m}}{\mathrm{s^2}} \approx 19.6 \frac{\mathrm{kN}}{\mathrm{m^3}} \tag{4}$$

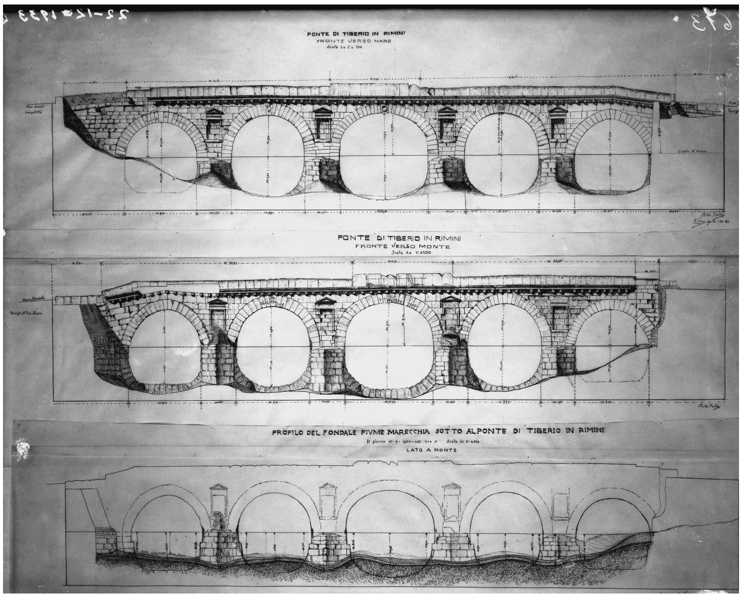

Figure 2. Drawing of the Tiberius Bridge in Rimini, Italy

The cross-sectional area of the semicircular arch is:

$$A = \frac{1}{2}\pi R^2 = \frac{1}{2}\pi(4.40)^2 \approx 30.4\ \mathrm{m}^2 \tag{5}$$

Thus, the total self-weight is:

$$P_{\text{self}} = A \cdot t \cdot \gamma = 30.4\ \mathrm{m}^2 \cdot 2.42\ \mathrm{m} \cdot 19.6\frac{\mathrm{kN}}{\mathrm{m}^3} \approx 1442.5\mathrm{kN} \tag{6}$$

This corresponds to an additional line load:

$$q_{\text{self}} = \frac{1442.5\mathrm{kN}}{8.80\ \mathrm{m}} \approx 164\frac{\mathrm{kN}}{\mathrm{m}} \tag{7}$$

The total load is therefore:

$$q_{\text{total}} = q + q_{\text{self}} \approx 422.4 + 164 = 586.4\frac{\mathrm{kN}}{\mathrm{m}} \tag{8}$$

The horizontal thrust at the base of the Tiberius Bridge arch, assuming a semicircular geometry, is given by:

$$H = \frac{q_{\text{total}} \cdot L^2}{8h} = \frac{586.4 \cdot (8.80)^2}{8 \cdot 4.40} \approx 1285.2\mathrm{kN} \tag{9}$$

The arch shows satisfactory geometric proportions for stability under the given load conditions, as the ratio between thickness and span is approximately 0.275. According to classical limit analysis methods [14], this configuration allows the line of thrust to remain within the middle third of the section, ensuring structural safety without tensile stresses [1].

5 Limit Analysis Using the Plastic Hinge Method

To verify the structural safety of the Tiberius Bridge arch in *opus caementicium*, a plastic analysis was performed using the classical three-hinge collapse mechanism. According to the limit state theory of masonry arches, collapse occurs when three plastic hinges form—typically at both supports and at the crown—allowing for a mechanism to develop [14, 15].

Assuming a semicircular geometry, the critical load at collapse is given by:

$$q_{\lim} = \frac{8M_p}{L^2} \tag{10}$$

where, q_{lim} is the maximum admissible line load before collapse (kN/m); M_p is the plastic moment capacity per unit width (kNm/m); L = 8.80 m is the span of the arch.

The plastic moment M_p for a rectangular section in pure compression is computed as:

$$M_p = \frac{\sigma_c \cdot t^2}{4} \tag{11}$$

where, σ_c = 9500 $\mathrm{kN/m^2}$ = compressive strength of the *opus caementicium*; t = 2.42 m = depth of the arch section.

Substituting the values:

$$M_p = \frac{9500 \cdot (2.42)^2}{4} = \frac{9500 \cdot 5.8564}{4} \approx 13908.9 \mathrm{kNm/m} \tag{12}$$

Then:

$$q_{1\mathrm{im}} = \frac{8 \cdot 13908.9}{(8.80)^2} = \frac{111271.2}{77.44} \approx 1436.6 \mathrm{kN/m} \tag{13}$$

Comparing with the actual load applied on the arch:

$$q_{\text{total}} = 586.4 \mathrm{kN/m} \Rightarrow \mathrm{FS} = \frac{q_{\lim}}{q_{\text{total}}} \approx \frac{1436.6}{586.4} \approx 2.45 \tag{14}$$

This demonstrates that the structure has a sufficient safety margin against collapse under the given loading. The line of thrust remains within the middle third of the section, and the geometry is consistent with stable masonry behavior as outlined in classical structural theory [14, 15].

6 Comparison of Mechanical and Physical Properties

This section presents a comparative analysis of selected cementitious materials based on three fundamental parameters: elastic modulus, compressive strength, and density. The materials considered include Ordinary Portland Cement (OPC), Fly Ash Cement, Pozzolanic Cement, UHPC, ECC, Glass Fiber Reinforced Concrete (GFRC), Aeternum HTE, and the ancient Roman *Opus Caementicium*.

6.1 Elastic Modulus Comparison

The elastic modulus E quantifies the stiffness of a material, i.e., its resistance to elastic deformation under load. As shown in Table 1, UHPC exhibits the highest elastic modulus, ranging from 45 to 50 GPa [8], followed by Aeternum HTE with an estimated range of 30 to 40 GPa [16]. Ordinary Portland Cement and Fly Ash Cement both present moderate stiffness, with values between 25 and 35 GPa [5, 17]. ECC and Pozzolanic Cement exhibit slightly lower values around 20 to 30 GPa [18, 19], while GFRC demonstrates a broader range (10 to 20 GPa), due to its composite nature [10]. *Opus Caementicium* shows the lowest modulus (8 to 12 GPa) [20], consistent with its historical composition and porosity.

Table 1. Test results of classification

Material	**Elastic Modulus** E **(GPa)**	**Compressive Strength** σ_c **(MPa)**	**Density** ρ $(\mathrm{kg/m^3})$
Ordinary Portland Cement	25–30 [5]	20–40 [5]	2300–2400 [5]
UHPC / UHPFRC	45–50 [8]	150–200 [8]	2300–2500 [8]
GFRC (GRC)	10–20 [10]	50-80 [10]	1900-2100 [10]
Aeternum HTE (est.)	30-40 [16]	70–190 [16]	2300–2400 [16]
Fly Ash Cement	25–35 [17]	30–50 (long term) [17]	2200–2400 [17]
Pozzolanic Cement	20–30 [18]	25–45 [18]	2200–2400 [21]
ECC	22 [19]	20–60 [19]	2200–2300 [19]
Opus Caementicium (Roman)	8–12 [20]	3–9.5 [20]	1800–2000 [20]

6.2 Density Comparison

Density ρ affects mechanical performance and construction logistics, such as dead load and transportation. Most modern cementitious materials, including OPC, UHPC, and Aeternum HTE, have densities in the range of 2300 to 2500 $\mathrm{kg/m^3}$ [5, 8, 16]. Fly Ash and Pozzolanic cements typically range from 2200 to 2400 $\mathrm{kg/m^3}$ [17, 18], while ECC falls slightly below, at 2200 to 2300 $\mathrm{kg/m^3}$ [19]. GFRC is noticeably lighter, ranging from 1900 to 2100 $\mathrm{kg/m^3}$ [10], a property often exploited in prefabrication. *Opus Caementicium*, composed of lime and volcanic ash, is the lightest, with a density of 1800 to 2000 $\mathrm{kg/m^3}$ [20].

7 Durability Comparison of Selected Cementitious Materials

Durability refers to the ability of a cementitious material to maintain its performance over time, particularly when exposed to environmental stressors such as moisture, freeze-thaw cycles, chlorides, sulfates, and carbonation. Table 1 presents the mechanical and physical properties of several commonly used cement-based materials, which can be interpreted in light of their expected durability.

Among modern materials, UHPC and UHPFRC are characterized by superior durability. Their dense microstructure and fiber reinforcement limit water and ion ingress, making them highly resistant to chemical attack and mechanical degradation [8]. Aeternum HTE, although still under development, is also designed for high resistance to environmental factors and aggressive exposure classes [16]. Similarly, ECC offers enhanced long-term durability due to its strain-hardening behavior and tight crack width control, which minimize pathways for harmful agents [19].

Fly Ash Cement and Pozzolanic Cement show improved durability compared to OPC, especially in terms of resistance to sulfate attack and reduction of chloride penetration. The presence of pozzolanic materials refines pore structure and contributes to continued hydration over time, leading to reduced permeability [17, 18]. These binders also contribute to lower heat of hydration and better chemical stability in the long term.

GFRC, while more often used in architectural applications, shows moderate durability. The inclusion of alkali-resistant glass fibers helps to preserve its mechanical performance, although its long-term resistance in harsh environments is generally lower than UHPC or ECC [12].

OPC, although the most widely used binder globally, exhibits only moderate durability. Its relatively high porosity and limited crack resistance increase its susceptibility to carbonation, freeze-thaw cycles, and chloride-induced corrosion of reinforcement [5]. In marine or chemically aggressive environments, OPC often requires additional protective measures or admixtures to meet service-life expectations.

In contrast, the ancient Roman binder known as *Opus Caementicium* has demonstrated remarkable long-term durability. Despite its low mechanical strength compared to modern materials, many Roman marine structures built with this cement have survived intact for over 2,000 years. This performance is attributed to the use of volcanic ash (pozzolana) and lime, which promote long-term mineralogical transformations and self-healing through continued crystallization processes [20]. Its ability to improve with time and form durable interfaces in wet conditions makes it unique among all historical and modern materials.

In summary, UHPC and ECC offer the highest durability among engineered modern concretes, with proven performance in aggressive environments. Fly ash and pozzolanic cements provide enhanced chemical resistance compared to OPC. GFRC offers moderate durability in non-structural applications, while *Opus Caementicium*, though ancient, remains an outstanding example of long-term material performance.

8 Resistance to Salt-Induced Corrosion

Salt-induced corrosion, particularly due to chloride ingress from marine environments or de-icing salts, is one of the most critical durability challenges for reinforced cementitious materials. The penetration of chlorides can lead to the depassivation of steel reinforcement and subsequent corrosion, resulting in cracking, spalling, and structural degradation.

Among the materials considered in Table 1, UHPC and UHPFRC exhibit exceptional resistance to chloride ingress due to their extremely low permeability and dense microstructure [8]. These properties reduce transport mechanisms such as diffusion and capillary suction, significantly delaying or even preventing the onset of corrosion in embedded steel. Their performance in marine structures and bridge decks exposed to de-icing salts has been well documented in both laboratory and field applications [8].

ECC also demonstrate good resistance to salt-induced corrosion, although their performance is somewhat lower than UHPC. Their advantage lies in tight crack width control, typically below 100 microns, which inhibits the penetration of chlorides even under cyclic loading and surface damage [19]. This characteristic is critical for maintaining long-term durability in coastal or cold-climate applications.

Fly Ash Cement and Pozzolanic Cement offer moderate improvement in chloride resistance compared to OPC, thanks to the pozzolanic reactions that consume calcium hydroxide and produce additional calcium silicate hydrates (C-S-H), which refine the pore structure [17, 18]. These materials reduce the connectivity of capillary pores, thereby slowing chloride diffusion. However, their performance still depends on curing, mix design, and the quality of supplementary materials used.

GFRC typically does not include internal steel reinforcement and is thus less vulnerable to corrosion issues. However, in the presence of embedded metallic elements or when used in hybrid systems, its durability depends on the integrity of the matrix and the alkali resistance of the glass fibers [10].

OPC is the most vulnerable to chloride-induced corrosion. Its relatively high permeability and susceptibility to cracking facilitate chloride ingress, especially in aggressive environments such as marine exposure zones or roads subjected to de-icing salts [5]. Protective coatings, corrosion inhibitors, or blended binders are often necessary when using OPC in such conditions.

Interestingly, *Opus Caementicium* (Roman concrete) has shown remarkable durability in marine environments, as evidenced by the preservation of ancient harbor structures. Its unique chemistry, involving volcanic ash and lime, leads to continued mineralogical transformations that fill microcracks and limit chloride penetration over centuries. Although not reinforced with steel, its inherent resistance to saltwater exposure offers valuable insights for the design of modern durable concretes (see Tables 1, 2, 3 and 4).

Table 2. Setting time and rheological properties

Material	t_{ini} (h)	t_{fin} (h)
GFRC (GRC)	2–4 [10]	6–12 [10]
ECC	0.07–4 [19]	4–28 [19]
Portland Cement	2–4 [22]	6–12 [22]
Pozzolanic Cement	4–6 [23, 24]	12–18 [24]
Opus Caementicium	>720 [25]	years [25]
Fly Ash Cement	4–8 [26]	12–24 [26]
UHPC / UHPFRC	4–10 [27]	7–24 [27]
Aeternum HTE	1–4* [27]	$\sim$ 24* [27]

Table 3. Chemical composition and functional properties

Material	Binder Type	Fiber / Impermeable
Portland Cement	Clinker + gypsum	no / no
Fly Ash Cement	Fly ash + clinker	no / partial
Pozzolanic Cement	Clinker + pozzolana	no / yes
UHPC / UHPFRC	Clinker + silica fume	steel 2–3% / yes
ECC	Cement + fly ash	polymer $\sim$ 2 % / yes
GFRC (GRC)	Cement + additives	glass 2–5%/ yes
Aeternum HTE	Proprietary blend	steel / poly/ yes
Opus Caementicium	Lime + volcanic ash	no / yes

Table 4. Mechanical properties and typical uses

Material	Strength	Durability	Uses
Portland Cement	High	Moderate	General
Fly Ash Cement	Low/High	High	Mass concrete
Pozzolanic Cement	Moderate	High	Marine, bridges
UHPC / UHPFRC	Very High	Excellent	Bridges, precast
ECC	Moderate/High	High	Seismic, overlays
GFRC (GRC)	Moderate	Moderate-High	Panels, facades
Aeternum HTE	High	Very High	Infrastructures
Opus Caementicium	Long-term	Outstanding	Harbors, aqueducts

9 Setting Time of *Opus Caementicium* and Its Implications on Construction Techniques

The setting time of *Opus Caementicium* is significantly longer compared to modern cementitious materials. Historical studies indicate that the initial set can take approximately 720 hours (about 30 days), while the final setting and hardening may extend over several years [20]. This prolonged setting and curing period is largely due to the slow pozzolanic reactions between volcanic ash and lime, which gradually develop the binder's strength and durability.

Such extended setting times had profound implications for ancient Roman construction techniques. Builders had to adopt phased construction schedules that allowed for long curing periods between the placement of successive layers or structural elements. This often involved the use of formworks and staged pours, enabling the material to achieve sufficient early strength before additional loads were applied.

Moreover, the slow hardening process contributed to the exceptional longevity of Roman concrete, as it permitted continuous mineralogical transformations and self-healing processes that enhanced durability over time. However, this also meant that rapid construction was not feasible, and projects required careful planning and extended timelines.

Understanding these unique setting characteristics provides valuable insights into the adaptation of construction practices to material properties and suggests potential strategies for developing modern sustainable binders with improved long-term performance but slower early strength development. The setting time of cementitious materials is a critical factor in determining their suitability for various construction techniques and scheduling constraints. Among all the materials considered, *Opus Caementicium* displays by far the slowest setting behavior. Historical sources and modern analyses indicate that its initial set could occur only after approximately 720 hours, or about 30 days, while the final hardening process may have extended over several years [20]. This extremely delayed setting is attributed to the slow kinetics of the pozzolanic reactions between volcanic ash and lime, without the presence of modern hydraulic phases or accelerators. As a result, the material required prolonged curing and a gradual gain in mechanical strength, which significantly influenced ancient Roman construction practices.

Unlike *Opus Caementicium*, modern materials are engineered for rapid setting and early strength development. OPC, for example, typically begins setting within 2 to 4 hours after mixing, with the final set achieved within 6 to 10 hours under standard conditions [5]. Fly ash and pozzolanic cements also exhibit slower setting compared to OPC, primarily due to delayed pozzolanic reactions. Nevertheless, the final setting usually occurs within 12 hours [17, 18], making them far more practical for modern construction timelines.

High-performance materials such as UHPC and ECC have adjustable setting times depending on formulation and curing condition. In general, these materials achieve initial set within 8 to 24 hours, especially when heat curing or chemical accelerators are applied [8, 19]. GFRC, commonly used for precast architectural elements, exhibits standard-setting behavior similar to OPC, though this may be affected by polymer additives and mix modifications [10].

The vastly different setting behavior of *Opus Caementicium* had major implications for construction techniques. Because of the long delay in hardening, Roman builders adopted a staged construction approach, pouring structures incrementally and allowing extended periods for early consolidation before proceeding with additional work. The need for long-term formwork and protection from environmental variation required careful planning and limited the pace of construction. However, the slow setting process also allowed for extended mineralogical development, contributing to the extraordinary long-term durability observed in Roman marine structures [20].

In contrast, modern cementitious systems are designed for efficiency and speed. Rapid setting allows for quicker formwork removal, accelerated construction schedules, and early loading of structural elements. This is particularly important in large-scale infrastructure, where time and cost constraints drive the adoption of fast-curing, high-performance materials. Yet, despite these advantages, the remarkable longevity of *Opus Caementicium* suggests that revisiting slow-setting systems—especially those that promote self-healing and long-term mineralogical transformations—may offer valuable insights into the development of next-generation sustainable concretes.

10 On the Maturation Times of Roman Concrete and Its Modern Implications

One of the main difficulties in replicating Roman concrete in a modern context lies in the very long maturation time required. Modern construction standards impose the use of binders that begin to set within a couple of days and reach full strength within approximately one month. Roman concrete, by contrast, required several years to consolidate fully.

To accommodate this slow-setting material, the Romans used structural techniques that involved the construction of supporting walls or facings made of stone, brick, or marble. These facings enclosed the core of concrete and served to protect it from environmental exposure during the long curing period. Various construction techniques were employed depending on the context, including *opus quadratum*, made of large squared stone blocks; *opus incertum*, made of irregular stones; *opus reticulatum*, with tuff bricks arranged in a diagonal grid; *opus latericium*, based on standard fired bricks; and *opus sectile*, involving marble elements.

The concrete was placed inside these facings, forming a stable and protected structural mass. This technique allowed the Romans to build highly durable structures even in harsh environments such as marine settings.

In maritime applications, the Romans employed a remarkable construction process to build underwater platforms and harbor foundations. They began by assembling wooden formworks shaped like open-bottomed boxes. These were made watertight using mortise and tenon joints. The formwork was then positioned on the sea floor at the construction site. Once in place, it was filled with a mixture of pozzolana, lime, and aggregates to form a hydraulic mortar. As the mortar began to react with seawater, the formwork would gradually settle, while divers continued to fill it from above until it reached the desired level. On this hardened base, the pier or mole was constructed using stone or brick elements.

This system, combined with the pozzolanic reaction between lime and volcanic ash, provided exceptional durability to Roman marine structures. Such construction methods are not compatible with the time constraints of modern industry, which do not allow for the slow maturation of concrete.

The next section presents a modern technique that, at least in theory, allows the use of slow-setting concrete inspired by Roman practice. This method employs additive manufacturing to create permanent, load-bearing formworks that remain in place, fulfilling the same protective and structural function as the external facings used in Roman construction.

11 An Additive Manufacturing Strategy for Constructing Ultra-Slow-Curing Concrete Structures Inspired by Roman Engineering

This study presents an innovative system for large-scale 3D printing of self-supporting formworks tailored to the slow-curing characteristics of Roman concrete. The goal is to enable continuous casting and environmental protection by integrating additive manufacturing with architectural design. The formwork remains in place after curing, analogous to the Opus Romanum technique, providing environmental shielding and reducing the need for additional cladding.

The proposed system uses a patented apparatus comprising a modular pseudo-matrix of compact 3D printers. These printers collaboratively fabricate a complex structure by producing smaller, puzzle-like components. The pseudo-matrix is a deformable, reconfigurable grid ("n × m"), adaptable to flat or curved surfaces, enabling printing on inclined planes and accommodating complex geometries. Elements are joined using interlocking features and various coupling methods such as adhesives or fasteners, allowing efficient assembly and minimizing human error.

To demonstrate the system, a reference structure inspired by the Ponte di Tiberio was designed. The structure's geometry is discretized into a set of inclined support planes, each assigned to a dedicated 3D printer module. The individual elements are printed and then assembled to form a series of self-supporting arches, mimicking the structural logic of the original Roman bridge. This approach ensures geometric fidelity and mechanical stability, while also showcasing the flexibility of the distributed fabrication system.

A virtual coordination system enables distributed manufacturing across separate physical locations, synchronizing multiple printing units to behave as a single apparatus.

The study highlights Roman concrete's favorable properties for seismic applications, notably its lower elastic modulus E, which enhances energy dissipation. In contrast, modern reinforcement techniques may introduce discontinuities under dynamic loads, increasing vulnerability.

Modern construction aims for a lifespan of 100–120 years; yet Roman structures exhibit exceptional longevity due to their material properties and design philosophy. This research proposes a method to revive those principles using contemporary digital fabrication techniques, promoting durability and sustainability in both heritage restoration and new construction.

12 Conclusions

Durability has been reaffirmed as a fundamental tenet of Roman engineering, aligning with Vitruvius' triad of architectural principles: *firmitas* (strength), *utilitas* (functionality), and *venustas* (beauty) [1]. Constructed in a context devoid of mechanized maintenance systems and reliant on manual labor, Roman structures were necessarily designed for extraordinary robustness and longevity.

The Tiberius Bridge in Rimini was examined as a representative case study of enduring structural performance. A simplified structural verification confirmed that, even after nearly two millennia of continuous service, the bridge retains a safety factor exceeding 2. Although direct records are lacking, historical accounts have indicated the possible passage of medium-duty vehicles, including military assets such as Sherman tanks, during the late stages of the Second World War, underscoring the exceptional load-bearing capacity of the structure.

The limitations of contemporary construction practices were subsequently analysed, particularly the widespread prioritization of early-age strength in modern binders at the expense of long-term durability. In contrast, Roman *opus caementicium* was characterized by the slow evolution of mechanical strength, enabled by pozzolanic reactions within a chemically stable matrix and protected by permanent formworks such as *opus quadratum* and *opus latericium*. These facings not only provided immediate structural support but also functioned as environmental shields, enhancing resistance to weathering and mechanical degradation.

To reconcile these ancient principles with contemporary demands, a modern construction methodology has been proposed. This approach involves the use of additive manufacturing to produce permanent, load-bearing formworks integrated with slow-setting cementitious binders. By mimicking the dual protective and structural functions of

Roman techniques within a digitally fabricated context, this strategy offers the potential to significantly extend service life, reduce life-cycle costs, and improve sustainability outcomes in infrastructure design.

Future research has been planned to experimentally validate this hybrid approach. Prototypes will be fabricated using slow-curing binders enclosed within 3D-printed permanent formworks, followed by comprehensive testing to assess their mechanical and durability performance in comparison to conventional reinforced concrete systems. Additionally, a detailed numerical simulation campaign will be conducted to model hydration kinetics, autogenous shrinkage, and strength development over extended timeframes, with a particular focus on the interactions between formwork geometry, thermal gradients, and internal curing dynamics.

Finally, full-scale implementation scenarios will be explored, including techno-economic and environmental impact assessments. Emphasis will be placed on the formulation of transferable design guidelines that can be embedded within modern regulatory frameworks such as the Eurocode, thereby enabling the practical adoption of ultra-durable construction practices rooted in ancient engineering philosophy yet enhanced by contemporary material science and fabrication technologies.

Author Contribution

Historical analysis and data gathering, E.L.; writing and calculations, L.P.; manuscript revision, E.L. and L.P. 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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