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Innovating Modern Cement by Harnessing Solutions from Ancient Roman Concrete

Luca Piancastelli*, Enrico Lorenzini

Dipartimento di Ingegneria Industriale (DIN), Università di Bologna Alma Mater Studiorum, 40136 Bologna, Italy

* Correspondence: Luca Piancastelli (luca.piancastelli@unibo.it)

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Abstract: This study presents a comprehensive comparison of modern cementitious composites, including UHPC, ECC, and GFRC, with traditional Ordinary Portland Cement (OPC) and ancient *Opus Caementicium* (Roman). Emphasis is placed on mechanical, physical, and rheological properties, as well as environmental and durability aspects. Advanced composites demonstrate superior short-termmechanical performance and improved impermeability, while Roman binders exhibit unparalleled long-term resilience in marine environments. Furthermore, the integration of pozzolanic materials and industrial by-products in contemporary mixes highlights ongoing efforts toward sustainable construction. Recent developments in China, including metakaolin–slag blends and nano-silica additives, as well as bio-inspired self-healing approaches, illustrate promising pathways for reducing carbon footprint and enhancing durability.

Keywords: Cementitious composites; Ultra-High Performance Concrete (UHPC); Engineered Cementitious Composite (ECC); Glass Fiber Reinforced Concrete (GFRC); Roman concrete; Durability; Pozzolanic reaction; Sustainability

1 Introduction

Opus Caementicium (Roman) represents a historical benchmark in construction materials, notable for its exceptional longevity and performance under harsh environmental conditions. Unlike modern Portland Cement, Roman formulations achieved remarkable durability, particularly in marine infrastructures, through a unique combination of pozzolanic reactions, lime-based binders, and low-temperature processing. Recent studies have highlighted several intrinsic advantages of Roman cement, including high corrosion resistance, low elastic modulus, compatibility with sustainable synthesis methods, and a capacity for self-healing.

The persistent structural integrity of Roman maritime constructions—many of which remain intact after over two millennia—has been linked to the development of rare crystalline phases such as Al-tobermorite and phillipsite in seawater-exposed matrices. These contribute to the formation of stable calcium-aluminum-silicate-hydrate (C-A-S-H) gels that resist chemical degradation. Furthermore, the use of volcanic ash and hot-mixed lime introduced beneficial heterogeneities and reactive phases that limited internal stress accumulation and enhanced mechanical resilience.

Contemporary research increasingly looks to ancient materials as models for sustainable and high-performance alternatives to conventional cement. However, despite advances in replicating some of Roman cement's corrosion resistance, key properties such as autogenous crack-healing and low elastic modulus remain difficult to reproduce at scale. This work aims to analyze these attributes in depth, evaluate the feasibility of reinforcing Roman-like binders with modern low-modulus fibers, and assess the potential for seismic-resilient applications with reduced environmental impact.

2 Comparison of Modern Cementitious Composites with Portland and Ancient Roman Binders

Recent developments in cementitious materials have introduced alternatives that significantly outperform Ordinary Portland Cement (OPC) in specific structural and durability aspects. As shown in Tables 1 and 2, advanced composites such as UHPC (Ultra-High Performance Concrete), ECC (Engineered Cementitious Composite), and GFRC (Glass Fiber Reinforced Concrete) exhibit higher compressive strengths, improved impermeability, and enhanced tensile ductility due to the integration of steel, polymer, or glass fibers. These properties are particularly beneficial for infrastructure exposed to aggressive environments, fatigue loading, or requiring slender sections.

Table 1. Mechanical and physical properties of cementitious materials

Material	E (GPa)	f_c (MPa)	ρ (kg/m^3)
OPC	25-30 [1]	20-40 [1]	2300-2400 [1]
UHPC / UHPFRC	45-50 [2]	150-200 [2]	2300-2500 [2]
ECC	22 [3]	20-60 [3]	2200-2300 [3]
GFRC (GRC)	10-20 [4]	50-80 [4]	1900-2100 [4]
Aeternum HTE (est.)	30-40 [5]	70-190 [5]	2300-2400 [5]
Opus Caementicium (Roman)	8-12 [6]	15-30 [6]	1800-2000 [6]

Table 2. Rheological and functional properties of cementitious materials

Material	t_{ini} (h)	t_{fin} (h)	Fiber / Impermeable
OPC	2-4 [7]	6-12 [7]	no / no
UHPC / UHPFRC	4-10 [7]	7-24 [7]	yes (2-3% steel) / yes
ECC	0.07-4 [3]	4-28 [3]	yes (polymer ∼2%) / yes
GFRC (GRC)	2-4 [4]	6-12 [4]	yes (glass 2-5%) / yes
Aeternum HTE (est.)	1-4* [7]	$\sim$ 24* [7]	yes (steel/poly) / yes
Opus Caementicium (Roman)	$>$ 720 [6]	years [6]	no / yes

Notes: *Opus Caementicium* (Roman) setting times are approximate and influenced by pozzolanic reactions. Values vary with volcanic ash content, lime quality, and environmental humidity [6, 8]

However, these modern materials also come with trade-offs, including longer and more variable setting times, higher costs, and stricter mixing and curing requirements. When compared to OPC, their environmental footprint may be reduced per unit strength but increased per unit volume due to specialized constituents. Compared to ancient *Opus Caementicium* (Roman) (see Figure 1), which relied on natural pozzolanic reactions and displayed remarkable long-term durability in marine environments, modern high-performance concretes offer superior short-term mechanical performance but have yet to demonstrate comparable resilience overmulti-century timescales. Nonetheless, materials like Aeternum HTE (see Tables 1 and 2) attempt to bridge this gap by combining the mechanical performance of UHPC with improved impermeability and controlled setting behavior, albeit based on extrapolated performance rather than archaeological longevity.

Figure 1. *Opus Caementicium* (Roman), Costantinople Wall. Creator: Johann H. Addicks (addicks@gmx.net). Image source: https://commons.wikimedia.org/wiki/File:Theodosianische_Landmauer_in_Istanbul.jpg. More info: https://it.wikipedia.org/wiki/Mura_di_Costantinopoli

3 Research on Pozzolana Replacement in Concrete

Pozzolanic materials have been widely used as supplementary cementitious materials (SCMs) to enhance the durability, mechanical properties, and sustainability of concrete [1]. However, the increasing demand for sustainable construction and the limited availability of natural pozzolanas have prompted extensive research into alternative materials that can effectively replace or partially substitute pozzolana in concrete mixtures.

Recent studies have explored various industrial by-products and natural materials, such as fly ash, blast furnace slag, rice husk ash, silica fume, and metakaolin, as potential pozzolana substitutes [9–11]. These alternatives not only contribute to the reduction of CO_2 emissions associated with Portland Cement production but also improve concrete properties such as compressive strength, resistance to chemical attack, and reduced permeability [12].

Moreover, advances in nanotechnology have enabled the development of nano-silica and other nano-sized materials to further enhance the pozzolanic activity and microstructure of concrete [13]. Bio-inspired materials and engineered pozzolanic blends are also emerging fields, aimed at mimicking the durability and self-healing properties observed in ancient Roman concretes [14].

Despite these advances, challenges remain regarding the long-term performance, cost-effectiveness, and large-scale availability of pozzolana replacements. Continued research is essential to optimize the composition and processing of these materials for widespread adoption in sustainable construction practices.

4 Comparison of Fly Ash, Portland, Pozzolanic, and *Opus Caementicium* (Roman) Materials

In response to the environmental impact of cement production, particularly in major producers such as China, there has been a significant shift toward the utilization of industrial byproducts like fly ash and blast furnace slag as supplementary cementitious materials. These efforts aim to reduce the carbon footprint and improve durability properties of cementitious composites in large-scale construction. China leads global production of fly ash cement blends, promoting sustainable construction practices while addressing emission regulations. Similar trends are observed worldwide, reflecting the growing interest in pozzolanic materials as alternatives to traditional Portland Cement.

Table 3. Comparison of fly ash, Portland, pozzolanic, and *Opus Caementicium* (Roman): Binder, reaction, and setting

Property	Fly Ash Cement	Portland Cement	Pozzolanic Cement
Primary binder	Fly ash + clinker	Clinker + gypsum	Clinker + natural pozzolana
Hydration reaction	Pozzolanic reaction (slow)	Hydration (fast)	Pozzolanic reaction
Setting time	Longer than Portland	Fast setting	Longer than Portland

Table 4. Comparison of fly ash, Portland, pozzolanic, and *Opus Caementicium* (Roman): Mechanical properties, durability, and uses

Property	Fly Ash Cement	Portland Cement	Pozzolanic Cement	*Opus Caementicium* (Roman)
Primary binder				Lime + volcanic ash
Hydration reaction				Pozzolanic reaction
Setting time				Slow setting
Early strength	Lower than Portland	High	Moderate	Low
Long-term strength	Comparable or higher	High	Comparable	Moderate to high
Durability	High (improved sulfate, chloride resistance)	Moderate	High	Very high (marine environments)
Permeability	Low (denser matrix)	Higher	Lower than Portland	Very low
Carbon footprint	Lower than Portland	High	Lower than Portland	Very low
Typical uses	Sustainable construction, mass concrete	General construction	Marine, bridges, durability-critical	Ancient structures, marine works

The comparative analysis of fly ash cement, Portland Cement, pozzolanic cement, and *Opus Caementicium* (Roman) reveals distinct differences in chemical composition, mechanical properties, and setting behaviors (Table 3). Fly ash cement utilizes a binder composed of fly ash and clinker, undergoing a slower pozzolanic hydration reaction compared to the fast hydration of Portland Cement, which is primarily clinker and gypsum based. Pozzolanic cement, containing clinker and natural pozzolana, also exhibits a pozzolanic reaction but shares intermediate setting times between fly ash and Portland Cement. *Opus Caementicium* (Roman), characterized by lime and volcanic ash, demonstrates the slowest setting time consistent with its traditional pozzolanic reaction.

Mechanically, fly ash cement shows elastic modulus values between 25-35 GPa and long-term compressive strengths of 30-50 MPa, comparable or superior to Portland Cement in durability and sulfate resistance (Table 4), while exhibiting lower early strength. Portland Cement offers rapid early strength development with similar compressive strength ranges but generally higher permeability and carbon footprint. Pozzolanic cement balances moderate early strength and long-term durability, with permeability and carbon footprint lower than Portland Cement but higher than *Opus Caementicium* (Roman). Roman cement stands out for its exceptional durability, especially in marine environments, with lower elastic modulus (15-25 GPa) and moderate compressive strength (15-30 MPa) (Table 5).

Table 5. Mechanical and physical properties of fly ash, Portland, pozzolanic, and *Opus Caementicium* (Roman)

Property	**Fly Ash Cement**	**Portland Cement**	**Pozzolanic Cement**	***Opus Caementicium* (Roman)**
Elastic modulus E (GPa)	25-35	25-30	20-30	8-12
Compressive strength f_c (MPa)	30-50	30-50 (early)	25-45	15-30
Density ρ (kg/m^3)	2200-2400	2300-2400	2200-2400	1800-2000

Table 6. Setting times of fly ash, Portland, pozzolanic, and *Opus Caementicium* (Roman)

Property	**Fly Ash Cement**	**Portland Cement**	**Pozzolanic Cement**	***Opus Caementicium* (Roman)**
Initial setting time t_{ini} (hours)	4-8	2-4	4-6	720
Final setting time t_{fin} (hours)	12-24	6-12	12-18	years

Setting time data corroborate the slower initial and final setting behavior of fly ash and pozzolanic cements relative to Portland Cement, with Roman cement exhibiting the longest setting periods (Table 6), reflective of its historical use in structures requiring gradual strength gain. These differences highlight the potential advantages of alternative cements in sustainable construction, emphasizing reduced environmental impact and enhanced durability, particularly in aggressive environments, while noting trade-offs in early strength and setting times compared to conventional Portland Cement.

5 Chinese Developments

5.1 Low-Carbon Cement with Metakaolin and Slag

Figure 2. The Three Gorges Dam on the Yangtze River, China. Source file: Le grand portage. Derivative work: Rehman, CC BY 2.0 (https://creativecommons.org/licenses/by/2.0), via Wikimedia Commons. More info: https://en.wikipedia.org/wiki/Three_Gorges_Dam

Several research initiatives in China have explored the potential of metakaolin and ground granulated blast furnace slag (GGBFS) as sustainable cementitious materials. These pozzolanic additives serve to reduce the clinker content of cement and thus significantly lower the associated CO_2 emissions. For example, Zhang et al. [15] demonstrated that a binary geopolymer system based on metakaolin and slag achieves ultra-high performance in terms of compressive strength and chloride resistance. Similarly, Wei et al. [16] investigated a ternary blend of magnesium slag, fly ash, and metakaolin, reporting that the material can attain over 80% of the mechanical strength of conventional mortar while reducing Portland Cement consumption by more than 40%.

While these findings underline China's commitment to alternative binders and decarbonized construction, there is no verified source confirming that Tongji University in Shanghai specifically developed a metakaolin–slag cement achieving a 60% reduction in CO_2 emissions compared to Portland Cement, nor that such material was used in parts of the Three Gorges Dam in 2022 (see Figure 2). Such claims require further corroboration through project-specific documentation or institutional reports.

5.2 Use of Pozzolanic Materials in Chinese Metro Infrastructure

Recent advancements in Chinese metro construction have demonstrated a growing reliance on pozzolanic-based materials—particularly fly ash and slag—in concrete formulations to enhance durability in humid and chloride-rich environments. Although no verifiable evidence has been found confirming the use of dedicated pozzolanic coatings in systems such as Beijing Subway Line 14, several high-profile metro systems in China—including those in Suzhou, Shenzhen, and Foshan—have adopted high-volume supplementary cementitious material (SCM) blends to improve impermeability and reduce cracking.

For example, Suzhou Metro incorporated a C35P8 concrete mix containing high volumes of Class II fly ash to reduce water ingress and shrinkage under high groundwater conditions [17]. Similarly, Shenzhen Metro Line 11 utilized a total of 55.7 million m^3 of blended concrete, with 39,400 t of fly ash and 69,000 t of slag, to meet 100-year durability standards while simultaneously reducing carbon emissions [18]. In Foshan, slag content between 35-40% and fly ash content of 15-20% enabled impermeability ratings of P10-P12 for tunnel linings [19]. These practices reflect China's strategic shift toward performance-based concrete design using industrial by-products, though surface-applied pozzolanic coatings have not been documented in public infrastructure records.

5.3 Application of Nano-Silica in Cementitious Materials

Research in China has extensively investigated the incorporation of nano-silica into cementitious mixes to improve mechanical strength and durability. Studies report that adding nano-SiO_2 at 4% by weight can enhance compressive and flexural strength by 10-20% compared to plain cementitious materials [20, 21]. For instance, laboratory tests showed increases in both compressive and flexural strength when cement mortar was modified with 4% nano-silica. Another study demonstrated that nano-SiO_2 reduced permeability and improved frost resistance by filling micro-pores under freeze-thaw cycles.

6 Assessment of Bio-Inspired Cement with Calcifying Bacteria

Recent research on microbially induced calcium carbonate precipitation (MICP) has demonstrated that certain bacterial species-such as Sporosarcina pasteurii-can facilitate self-healing in cementitious materials by precipitating calcite [22, 23]. These bio-inspired approaches mimic natural mineralization processes and can enhance crack closure and durability in concrete.

Although laboratory and pilot-scale studies show promising results in combining bacterial calcite precipitation with cementitious binders, including metakaolin or artificial pozzolana additives analogous to Roman pozzolanic mechanisms, widespread practical application remains under development [22].

7 Advantages of Low Elastic Modulus in Seismic-Resistant Structures

In seismic design, the elastic modulus (E) of structural materials plays a crucial role in controlling the dynamic response of buildings. Alower elasticmodulus generally leads to increased deformability, which can be advantageous in seismic-resistant structures by reducing the acceleration demands and allowing for better energy dissipation. According to the simplified single-degree-of-freedom (SDOF) model, the fundamental period of vibration T is given by

$$T = 2\pi\sqrt{\frac{m}{k}} = 2\pi\sqrt{\frac{m}{\alpha EA/L}} \tag{1}$$

where, m is the mass, k is the lateral stiffness, α is a geometric factor, A is the cross-sectional area, and L is the height of the structural element. As E decreases, the natural period T increases, shifting the structure's response to a lower spectral acceleration range according to typical seismic response spectra [24].

For example, consider a cantilever beam representing a structural column with length L=3 m, cross-sectional area A=0.02 m^2, and mass m=1000 kg. Using two materials with elastic moduli E_1=30 GPa (conventional concrete) and E_2=15 GPa (low-modulus cementitious composite), the respective natural periods are:

$$T_1 = 2\pi\sqrt{\frac{mL}{\alpha E_1 A}} \approx 0.72 \text{ s} \quad (2)$$

$$T_2 = 2\pi\sqrt{\frac{mL}{\alpha E_2 A}} \approx 1.02 \text{ s} \quad (3)$$

assuming α=12 for a fixed-free cantilever beam [25].

This increase in period can reduce seismic forces according to the design acceleration $\alpha(T)$ from seismic spectra, potentially lowering base shear and structural demand. Furthermore, materials with lower E often exhibit higher strain capacity and energy absorption, contributing to improved ductility and damage tolerance under seismic loading [26]. Thus, the use of low-modulus cementitious composites offers a promising strategy to enhance seismic resilience by combining favorable dynamic characteristics with material ductility.

8 Discussion

This work highlights several intrinsic strengths of *Opus Caementicium* (Roman), including its outstanding corrosion resistance, low elastic modulus, compatibility with low-temperature manufacturing, and self-healing capacity.

The exceptional long-term durability of Roman marine structures, such as piers and harbors, is primarily attributed to their corrosion resistance. This is linked to the formation of Al-tobermorite and phillipsite in seawater-exposed matrices, resulting in stable, low-crystalline calcium-aluminum-silicate-hydrate (C-A-S-H) gels that resist chloride-induced degradation [27].

Moreover, the low elastic modulus of the volcanic-ash-based binder limits internal stress accumulation, enhancing fracture toughness and mechanical resilience [28–30].

Unlike modern Portland Cement, Roman mixtures were often hot-mixed with quicklime, producing lime clasts rich in reactive, nanoporous $CaCO_3$. This not only accelerated setting but also enabled autogenous crack-healing through re-crystallization [31].

Low-temperature processing further reduced energy demand and CO_2 emissions, making Roman cement an early example of sustainable construction technology [32].

Currently, only the corrosion resistance aspect has been reliably replicated in modern formulations. Other desirable features—such as self-healing behavior, low elastic modulus, and low-temperature synthesis—require further research, especially in the context of seismic reinforcement.

One promising strategy involves reinforcing Roman-like binders with low-modulus fibers, such as glass fibers or superplastic alloys. Glass fibers improve ductility but pose health concerns during handling and cutting: long, biopersistent fibers are classified as Group 2B (possibly carcinogenic), while short, biosoluble types are less hazardous (Group 3) [33, 34]. Superplastic alloy fibers, although non-toxic and effective, face limitations due to high production costs and limited commercial availability [28].

Future work should explore fiber-reinforced Roman binders with balanced cost-performance profiles, aiming at scalable solutions for seismic applications.

9 Conclusions

The comparative analysis confirms that modern cementitious composites surpass OPC in mechanical strength and durability-related properties, albeit with increased complexity and cost. Ancient Roman concretes maintain exceptional long-term performance, particularly in aggressive environments, attributable to their unique pozzolanic chemistry and slow-setting behavior. The adoption of supplementary cementitious materials such as fly ash, slag, and metakaolin, especially in Chinese infrastructure projects, demonstrates a global trend towards more sustainable binders with reduced environmental impact. Innovations like nano-silica incorporation and microbially induced calcite precipitation offer additional avenues to enhance material performance and durability. Future research should focus on bridging the gap between the longevity of ancient materials and the high-performance demands of modern applications, ensuring environmental sustainability without compromising structural integrity.

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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