Durability-Oriented Construction Using Roman-Type Concrete and Permanent 3D-Printed Formworks

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Abstract: The long-term durability of reinforced concrete infrastructure remains a critical challenge, as conventional Portland cement and carbon steel systems are inherently vulnerable to corrosion and environmental degradation. Roman concrete demonstrates exceptional longevity due to slow hydration kinetics, pozzolanic reactions, and self-healing mechanisms, but its integration into modern construction is limited by incompatibility with rapid construction workflows. At the same time, additive manufacturing has enabled advanced geometric control, while rarely addressing durability as a primary design objective. This study proposes a durability-driven construction system integrating Roman-type concrete, stainless steel reinforcement, and permanent additively manufactured thermoplastic formworks. Rather than acting as a temporary construction aid, the formwork is redefined as a permanent protective enclosure that sustains early-age loads, accommodates slow curing, and provides long-term environmental shielding. Stainless steel reinforcement is employed to mitigate corrosion, the dominant degradation mechanism. The system is evaluated using a multi-level methodology that combines material compatibility analysis, finite-element modelling of early-age conditions, and architectural-scale demonstration. The critical pre- and post-casting phases are analysed by modelling the fresh concrete as a fluid-like load acting on the permanent formwork, which represents the load-bearing component prior to setting. A segmented dome inspired by the Pantheon is used to demonstrate scalability and system integration. While direct validation over century-scale timeframes is impractical, the results show that the proposed system satisfies necessary conditions for extended service life, providing a scientifically grounded framework for durability-oriented construction using additive manufacturing.

Keywords: Durability-oriented construction; Roman-type concrete; Permanent formwork; 3D printing; Polyether ether ketone; Hydrostatic pressure; Finite element analysis; Architectural shells

1 Introduction

The long-term durability of reinforced concrete structures remains one of the most persistent challenges in construction engineering. Despite continuous advancements in cement chemistry, admixtures, and protective technologies, modern reinforced concrete systems frequently fail to achieve their intended service life. Corrosion of carbon steel reinforcement, loss of alkalinity due to carbonation, chloride ingress, and crack propagation driven by shrinkage and thermal effects collectively represent systemic vulnerabilities rather than isolated defects. These mechanisms lead to escalating maintenance requirements and premature rehabilitation, raising fundamental questions about the suitability of prevailing material and construction paradigms for long-term infrastructure. Existing research has primarily addressed durability through localized or additive solutions, such as corrosion inhibitors, surface coatings, cathodic protection, or modified cement formulations. While effective under controlled conditions, these strategies treat durability as an external constraint imposed after the primary structural and construction decisions have been made. As a consequence, durability is rarely embedded as a governing design variable at the material-process-structure level. This limitation is particularly evident in environments requiring extended service life with minimal maintenance, such as heritage contexts, marine infrastructure, or long-span architectural elements. In contrast, Roman concrete-based constructions demonstrate that durability can emerge naturally when material chemistry, structural form, and construction methodology are coherently aligned. Roman concrete exhibits slow hydration kinetics, long-term pozzolanic reactions, and intrinsic self-healing mechanisms, resulting in progressive mechanical stabilization

over extended timeframes. However, these same characteristics conflict with contemporary construction workflows optimized for rapid strength development and early demoulding. As a result, the integration of Roman concrete or similar slow-curing binders into modern practice remains largely unexplored beyond laboratory-scale material studies. Concurrently, additive manufacturing has introduced unprecedented control over geometry, material placement, and functional integration in construction. Large-format three-dimensional printing has been successfully applied to both cementitious materials and polymer-based formwork, enabling complex geometries that are unattainable with conventional techniques. Nevertheless, most existing studies prioritize geometric freedom, automation, or production speed, while long-term performance metrics such as durability, environmental protection, and compatibility with slow-evolving materials are seldom addressed. Furthermore, formwork is almost universally treated as a temporary element, removed after casting and excluded from durability considerations. These observations reveal a critical research gap: the absence of construction systems in which durability is treated as a primary, verifiable design objective achieved through the deliberate integration of material selection, reinforcement strategy, and fabrication method. In particular, there is limited understanding of how slow-curing, high-durability concretes can be effectively cast and protected using permanent, digitally fabricated formworks, and how reinforcement systems can be selected to support extended service life without reintroducing dominant degradation mechanisms. This study proposes an integrated construction concept combining Roman concrete, stainless steel reinforcement, and permanent 3D-printed thermoplastic formworks. The central hypothesis is that durability can be enhanced at the system level by: (i) employing a cementitious matrix whose mechanical and chemical stability improves over time; (ii) adopting corrosion-resistant reinforcement to suppress the primary degradation pathway of modern reinforced concrete; and (iii) redefining the formwork as a permanent protective enclosure rather than a disposable construction aid. The research questions addressed in this work are formulated to enable explicit validation. First, the feasibility of producing self-supporting, large-scale formwork through distributed additive manufacturing is assessed with respect to geometric accuracy, assembly tolerances, and load-bearing capacity during casting and curing. Second, the compatibility between permanent formwork and slow-curing Roman concrete is evaluated using qualitative and quantitative indicators, including formwork deformation under hydrostatic pressure, accommodation of volumetric shrinkage, and preservation of the designed geometry after curing. Third, the contribution of the integrated system to durability is examined through proxy performance metrics, such as reduction of exposed concrete surface area, elimination of secondary protective coatings, and mitigation of corrosion-prone interfaces. Given the millennial timescales associated with Roman concrete, direct experimental verification of long-term durability is inherently impractical. Consequently, this study adopts a multi-level validation approach that combines analytical reasoning, numerical simulations, material-compatibility analysis, and architectural-scale demonstrators. Durability is therefore assessed through indirect yet scientifically grounded criteria, including: (i) chemical compatibility between binder, reinforcement, and formwork materials; (ii) mechanical compatibility in terms of elastic modulus and deformation behaviour during curing; (iii) environmental shielding effectiveness provided by the permanent formwork; and (iv) constructability and reproducibility of the proposed system within contemporary fabrication constraints. These criteria are applied through the design and fabrication of modular, 3D-printed formworks incorporating integrated casting channels, vibration access points, and mechanical interlocks. A segmented dome inspired by Roman precedents is used as a demonstrator to validate geometric feasibility, assembly logic, and construction sequencing at the architectural component scale. While the case study does not claim direct measurement of century-scale performance, it provides verifiable evidence that the proposed system satisfies necessary conditions for long-term durability as defined by current materials science and structural engineering knowledge. By explicitly defining validation metrics and aligning them with the stated research questions, this work advances beyond descriptive comparison of materials and technologies. It contributes a durability-driven framework for integrating additive manufacturing with high-performance cementitious systems, offering a scientifically grounded pathway toward construction practices oriented to extended service life rather than short-term efficiency [1–3]. The durability-driven construction concept proposed in this study is schematically summarized in Figure 1. The figure illustrates the integration of Roman concrete, stainless steel reinforcement, and permanent 3D-printed thermoplastic formwork as a unified material–process system, in which durability emerges from chemical compatibility, controlled mechanical accommodation during curing, and long-term environmental shielding, rather than from isolated material optimization.

Roman concrete, stainless steel reinforcement, and permanent 3D-printed thermoplastic formwork are integrated as a single material-process system. Durability emerges from their combined chemical compatibility, mechanical interaction during curing, and long-term protection against environmental exposure. The figure shows the main environmental agents acting on the structure, including water, the marine environment, solar radiation, and wind. The light-blue containment structure encloses the Roman concrete core (gray), shielding it from external agents and providing mechanical support during the initial setting and long-term curing phases. Corrosion-resistant reinforcement bars, shown in dark gray, are used sparingly to minimize discontinuities within the load-bearing system.
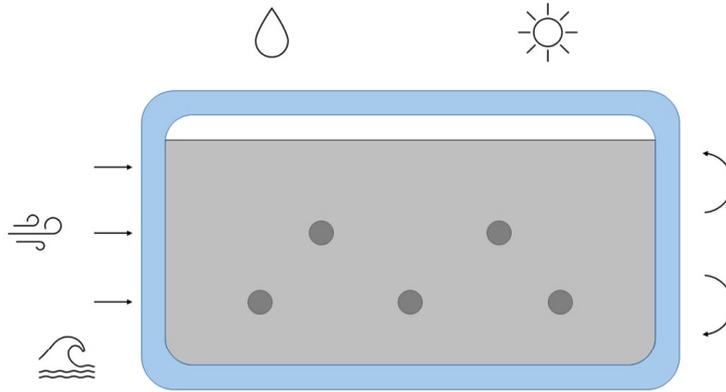
Figure 1. Schematic overview of the proposed durability-driven construction system

2 Methodology

2.1 System-Level Design Framework

The proposed construction system was developed following a durability-driven design approach, in which material selection, reinforcement strategy, and fabrication method were treated as interdependent variables. Rather than optimizing individual components in isolation, the system was designed to satisfy a set of necessary conditions for long-term durability, derived from established materials science and structural engineering principles. The mechanical interaction between the permanent formwork and the fresh Roman concrete during casting and early curing is schematically illustrated in Figure 2. The figure highlights the role of the thermoplastic shell in sustaining hydrostatic pressure and accommodating controlled elastic deformation, while preserving the target geometry defined at the design stage. Importantly, the formwork is conceived exclusively as an early-stage support and protective enclosure; therefore, its contribution is excluded from long-term structural load calculations.
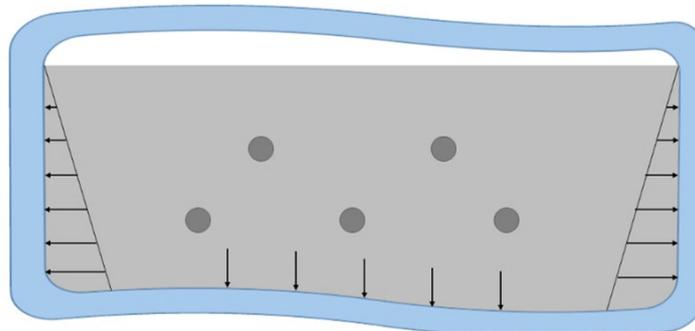

Figure 2. Sectional view of the formwork during casting and curing of Roman concrete

The figure illustrates the loads acting on the permanent polyether ether ketone (PEEK) formwork during the early curing phase. The thermoplastic shell resists hydrostatic pressure, accommodates elastic deformation, and preserves the target geometry throughout the extended curing period. Lateral and bottom vertical vectors indicate the pressures acting on the formwork, while the triangular distribution represents hydrostatic loading. The upper void indicates the likely formation of trapped air and other non-condensable gases, as well as shrinkage effects. The structural contribution of the formwork is limited to early-stage support and is not considered in long-term load-bearing calculations.

2.2 Additive Manufacturing of Permanent Formworks

Large-format thermoplastic formworks were fabricated via distributed additive manufacturing. Their accuracy, assembly tolerances, and repeatability were quantified by dimensional measurements.

2.3 Casting and Curing Compatibility Assessment

The interaction between the printed formwork and the Roman concrete was evaluated during casting and curing. Formwork deformation under hydrostatic pressure, volumetric shrinkage accommodation, and preservation of the

target geometry were monitored qualitatively and analytically.

2.4 Reinforcement and Material Compatibility Analysis

Stainless steel reinforcement was selected based on corrosion resistance and chemical compatibility with lime-pozzolan binders. Compatibility was assessed using literature-based corrosion models and comparisons with conventional carbon-steel systems.

2.5 Validation Through an Architectural-Scale Demonstrator

A segmented dome was designed as an architectural-scale demonstrator. The case study was used to validate constructability, assembly logic, and system integration rather than to claim direct long-term durability performance.

3 Comparison of 3D-Printable Polymers for Fused Deposition Modelling

A wide range of thermoplastic polymers can be processed through fused deposition modelling (FDM), each offering a distinct balance of processability, mechanical performance, and thermal stability (Table 1). Common printable materials include polylactic acid (PLA), acrylonitrile-butadiene-styrene (ABS), polyethylene terephthalate glycol (PETG), and polyamides (PA6, PA12). More advanced high-performance materials such as polyetherimide (PEI, marketed as ULTEM) and PEEK extend the range of printable polymers into aerospace and structural applications [4, 5].

Among these, PEEK represents the pinnacle of mechanical and thermal performance currently achievable with thermoplastic FDM. It exhibits tensile and compressive strengths comparable to medium-carbon structural steels, a melting temperature near 343°C, and outstanding resistance to chemical and environmental degradation [6, 7]. In contrast, low-cost polymers such as PLA and ABS, while easy to process, suffer from limited thermal stability and mechanical fatigue resistance. PEI and polyamide filaments bridge the gap between commodity and high-performance materials, providing higher toughness and thermal endurance at moderate processing temperatures [5, 8].

However, the superior performance of PEEK comes at the cost of demanding printing conditions, requiring nozzle temperatures above 400°C and a heated build chamber exceeding 150°C to ensure adequate layer adhesion and crystallization. Despite these challenges, PEEK remains the benchmark material for structural 3D-printed components where strength-to-weight ratio, long-term stability, and chemical resistance are essential.

From a mechanical standpoint, PEEK clearly outperforms other printable polymers in both static and fatigue strength, while also maintaining excellent chemical and environmental stability. PEI provides a more processable but slightly less robust alternative. Consequently, PEEK remains the best-performing 3D-printable thermoplastic currently available, particularly for aerospace and high-stress mechanical applications, albeit at higher cost and processing complexity [4–6].

Table 1. Mechanical properties of common fused deposition modelling (FDM) polymers

Material	σ_t [MPa]	E [GPa]	ρ [g/cm^3]	Remarks
Polylactic acid (PLA)	55–65	3.0	1.25	Easy print; brittle; low heat resist
Acrylonitrile-butadiene-styrene (ABS)	35–45	2.0	1.04	Tough; moderate impact; warping issues
Polyethylene terephthalate glycol (PETG)	50–60	2.1	1.27	Chem. resist.; ductile; smooth finish
Polyamides (PA12)	70–80	1.7	1.01	High toughness; hygroscopic
Polyetherimide (PEI or ULTEM)	90–100	2.8	1.27	Aerospace-grade; high-temp use
Polyether ether ketone (PEEK)	90–110 (up to 250)	4.0–4.5 (up to 18)	1.30	Aerospace-grade; difficult printing

3.1 Mechanical Properties of 3D-Printed Polyether Ether Ketone

Three-dimensional printing of PEEK has become a viable manufacturing route for lightweight structural components in aerospace and mechanical systems. The polymer's semi-crystalline nature, combined with its high melting temperature and exceptional thermal stability, allows it to maintain mechanical integrity even under demanding service conditions [6, 9].

Additive manufacturing processes such as fused filament fabrication and selective laser sintering have demonstrated that 3D-printed PEEK can achieve tensile and compressive strengths comparable to those of medium-carbon structural steels (e.g., 0.3–0.5 wt% C, typically 700–1000 MPa). Experimental results have reported tensile strengths of 90–110 MPa for printed PEEK specimens and up to 250 MPa for optimized, annealed, or carbon-fiber-reinforced PEEK [7, 10]. When converted into specific strength (strength-to-density ratio), 3D-printed PEEK often equals or exceeds that of conventional steels, owing to its low density of approximately 1.3 g/cm³. However, the elastic modulus of PEEK is substantially lower than that of metals. While mild and medium-carbon steels typically exhibit Young's modulus around 200 GPa, 3D-printed PEEK shows modulus values ranging from 3.5 to 4.5 GPa for unfilled grades and up to 18 GPa for carbon-fiber-reinforced composites [6, 8]. This large disparity in stiffness limits the polymer's

use in applications requiring high rigidity or precise dimensional stability under load but remains acceptable for lightweight structures and non-load-bearing housings. The mechanical behaviour of printed PEEK depends strongly on printing parameters, degree of crystallinity, and interlayer adhesion. Optimized nozzle temperatures (typically 400–430°C), build chamber control, and post-print annealing significantly enhance crystallization and interlaminar bonding, improving strength and fatigue resistance. Studies have shown that proper thermal management during printing can increase tensile strength by more than 30% compared with unoptimized conditions [7, 8]. Moreover, PEEK retains excellent toughness, creep resistance, and fatigue strength even after long-term exposure to elevated temperatures (up to to elevated temperatures (up to 250°C), which is unusual among engineering thermoplastics. This makes it suitable for parts subject to cyclic loading, vibration, or moderate dynamic stress in propulsion or structural assemblies. Its fracture toughness is typically between 3 and 4 MPa $\cdot$ m$^{1/2}$, while its fatigue endurance limit exceeds 50% of its static tensile strength in air [6].

In summary, 3D-printed PEEK offers a strength comparable to that of medium-carbon steels, along with low weight, chemical resistance, and thermal stability. Despite its lower stiffness, it remains a promising material for aerospace components, housings, and brackets, particularly when weight reduction and resistance to environmental degradation are prioritized over elastic rigidity.

3.2 Compatibility of Polyether Ether Ketone with Concrete

PEEK exhibits a low moisture absorption rate ($<0.14\%$ or $<0.1\%$), a key property that enables the material to maintain stable mechanical, thermal, and electrical characteristics even in humid environments or in direct contact with water. This performance is further supported by its excellent resistance to hydrolysis. A major advantage of PEEK is its dimensional stability: the minimal moisture uptake prevents material swelling, thereby ensuring the dimensional integrity of components made from PEEK. Furthermore, both the electrical and mechanical properties remain consistent under varying humidity levels or full immersion in liquids, making PEEK highly suitable for electronic applications and aqueous environments. The material also offers strong chemical resistance, not only to moisture but also to a broad range of chemical agents, including acids and solvents. This enhances its usability in harsh operating conditions. In terms of processing implications, despite its low moisture absorption, PEEK must be dried before molding (typically for 2–4 hours at 150–160°C) to eliminate residual moisture that could interfere with manufacturing. Once processed, the material does not require special protection against moisture and can be used in continuous immersion in hot water or steam without degradation of performance.

3.3 Durability of Polyether Ether Ketone and Weathering Resistance

PEEK is a high-performance semi-crystalline thermoplastic characterized by exceptional mechanical strength, thermal stability, and chemical inertness. These properties, combined with its aromatic backbone and ketone linkages, contribute to a remarkably high resistance to oxidative degradation and photochemical ageing. Consequently, PEEK has become a reference material in high-demand aerospace and mechanical applications where long-term reliability is critical [11, 12]. The long-term stability of PEEK depends primarily on the mechanisms of thermo-oxidative degradation, UV photodegradation, creep deformation, and, to a lesser extent, moisture and hydrolytic effects. In ambient conditions, the polymer absorbs less than 0.1% of moisture by weight, effectively eliminating dimensional drift and preserving dielectric properties even after prolonged exposure. Thermo-oxidative degradation becomes significant only above 250°C, while mechanical creep remains minimal under moderate stress and temperature levels [13]. When exposed to ultraviolet radiation, PEEK demonstrates superior surface stability compared with polyamides and polycarbonates, owing to its aromatic structure. Surface oxidation and discoloration may occur after long exposure, but bulk mechanical integrity is retained for extended periods. The addition of stabilizers or surface coatings further enhances weathering resistance, making PEEK suitable for outdoor and aerospace service environments [14, 15]. Accelerated ageing tests have been conducted to estimate the service life of PEEK under elevated temperatures, humidity, and radiation. Extrapolation using Arrhenius or time-temperature superposition models suggest potential service durations far exceeding those of conventional polymers. For example, studies on cable insulation materials have reported an expected lifetime of approximately 70 years at 90°C, implying much longer durability at ambient conditions [16]. Manufacturer data from Victrex and Solvay further report projected shelf-lives beyond one century for stored components kept under controlled ambient conditions, based on multi-year accelerated ageing correlations [11, 12].

Despite these encouraging results, extrapolations to extreme timeframes—such as 100 to 200 years—must be treated with caution. Laboratory acceleration procedures cannot perfectly replicate the complex synergy of natural weathering factors, and reciprocity failures are frequently observed [15]. As noted in polymer ageing studies [17], prediction accuracy declines exponentially with increasing extrapolation distance from empirical data. Nevertheless, under protected conditions—that is, the absence of UV exposure, stable temperature, limited oxygen diffusion, and low sustained stress—theoretical projections of structural integrity lasting a century or more remain plausible [11, 12]. From an engineering standpoint, it is therefore recommended that claims of centennial durability be accompanied

by explicit assumptions regarding operational environments and maintenance. When combined with appropriate surface protection, PEEK's mechanical and chemical stability may extend beyond 100 years, fulfilling requirements for ultra-long-term structural components [11, 14, 15].

3.4 Permanent Joining and Protective Coating Strategies for Polyether Ether Ketone Structures in Harsh Environments

PEEK is a high-performance thermoplastic polymer distinguished by its exceptional mechanical strength, chemical resistance, and thermal stability, which make it an ideal candidate for advanced structural and aerospace applications. Despite its robustness, PEEK presents notable challenges in terms of joinability due to its high crystallinity and low surface energy, which limit both adhesion and weldability. However, several effective techniques have been developed to achieve reliable bonding between PEEK components.

Thermoplastic welding processes—such as laser welding, ultrasonic welding, friction welding, and resistance welding—are particularly suited to PEEK, as they exploit localized heating above the polymer's melting point (approximately 343°C) to achieve molecular interdiffusion at the interface, resulting in joints with mechanical strength comparable to the bulk material. In parallel, surface activation methods such as plasma treatment, chemical etching, or corona discharge significantly increase the polymer's surface energy, thereby improving adhesion to structural adhesives. When properly treated, PEEK can be bonded with high-temperature-resistant epoxy or polyimide adhesives, resulting in durable, chemically stable joints. The combination of thermal weldability and adhesive bondability enables versatile manufacturing strategies, especially in additive manufacturing and hybrid structural systems, where PEEK elements can be assembled, repaired, or integrated into larger composite frameworks without compromising performance or durability. Protective coating strategies for PEEK structures are essential to ensure long-term performance in harsh environmental conditions, including exposure to ultraviolet radiation, moisture, saline atmospheres, and chemical agents. Although PEEK inherently exhibits excellent resistance to corrosion, oxidation, and hydrolysis, its surface can still undergo gradual degradation under prolonged thermal or radiative stress [18, 19]. To enhance durability and maintain surface integrity, various coating systems have been developed, such as fluoropolymer, ceramic, and metallic thin films, which provide additional barriers against wear, oxidation, and environmental attack [20]. Advanced surface treatments, including plasma-assisted deposition, chemical vapor deposition, and sol-gel coatings, can further improve coating adhesion and create multifunctional protective layers with hydrophobic, anti-fouling, or UV-resistant properties [21]. In addition to thin-film coatings, PEEK can be effectively painted to enhance environmental protection and aesthetic quality. However, due to its high chemical inertness and low surface energy, direct paint adhesion is difficult without prior surface preparation. Treatments such as plasma activation, sulfuric acid chemical etching, or controlled mechanical abrasion increase surface polarity and roughness, thereby promoting strong interfacial bonding with coating materials [22]. Once properly prepared, PEEK can be coated with epoxy, polyurethane, or silicone formulations, enhancing resistance to UV, humidity, and corrosion. Multilayer coatings ensure long-term adhesion and stability, protecting PEEK's structural and mechanical integrity and extending its service life in aerospace, marine, and industrial applications.

3.5 3D Printing with Polyether Ether Ketone

Due to its high melting temperature (approximately 343°C), PEEK requires specialized high-temperature extrusion systems and heated build chambers for successful processing (Table 2). These requirements make its application in FDM particularly challenging. Recent advances in additive manufacturing have enabled the use of PEEK in precise, mechanically demanding applications, such as custom formwork for structural elements. Commercial high-temperature FDM printers can now achieve dimensional tolerances of better than ±0.1 mm under controlled conditions, depending on the geometry and thermal management of the build environment. Build volumes of up to 1000 mm × 1000 mm × 1000 mm are available on industrial-grade machines, enabling the fabrication of large-scale components suitable for construction or prototyping [23, 24]. Using movable tables can triple the working volume.

Table 2. Thermal and processing characteristics of fused deposition modelling (FDM) polymers

Material	T_g [°C]	T_m [°C]	Processing Notes
Polylactic acid (PLA)	60	180	Low T print; low warp; poor outdoor perf
Acrylonitrile-butadiene-styrene (ABS)	105	220	Heated bed req.; prone to cracking
Polyethylene terephthalate glycol (PETG)	80	250	Moderate T; good adhesion
Polyamides (PA12)	50	180	Needs dry env.; flexible
Polyetherimide (PEI or ULTEM)	217	340	High T printer req. (>350°C)
Polyether ether ketone (PEEK)	143	343	Chamber >150°C; nozzle >400°C

4 A New Proposal: Structural Polyether Ether Ketone Formworks for Stainless-Reinforced Roman Concrete

The proposed approach introduces the use of a high-performance thermoplastic, such as PEEK, to create structural formwork capable of sustaining both self-weight and environmental loads during the casting and curing of stainless-reinforced Roman concrete. Although PEEK exhibits a much lower elastic modulus than traditional construction steels, its excellent strength-to-weight ratio, thermal stability, and chemical resistance make it a suitable candidate for formwork applications in demanding environments [18]. The intrinsic flexibility of PEEK allows the formwork to accommodate deformations induced by hydrostatic pressure during casting and to adapt progressively to the volumetric shrinkage of Roman concrete throughout its long curing process, which may extend over one year. As illustrated in the following section, the formwork can be fabricated as modular 3D-printed segments incorporating predesigned structural elements such as ribs, tie rods, vent holes for air release, access points for concrete vibrators, and interlocking features for alignment and assembly. These segments can be thermally welded together, forming joints that are only partially watertight, similar to traditional timber or metal formworks [19]. During casting, the thermoplastic formwork undergoes controlled elastic deformation under hydrostatic load while maintaining sufficient stiffness to ensure geometric stability. The final geometry of the structure must therefore be optimized using numerical simulations to compensate for deformation and shrinkage, ensuring that load-bearing surfaces, such as bridge decks, remain level and structurally efficient after curing [21]. The surface of the thermoplastic segments can be pretreated to enhance adhesion and containment of the cementitious matrix, for instance through plasma activation or chemical etching. Exposed areas may be further protected by weather-resistant coatings to ensure long-term durability under environmental exposure [20]. The overall computational process presents no particular difficulties, as commercially available finite element and structural simulation software can be effectively used to predict both the deformation behaviour of the PEEK formwork and the curing dynamics of Roman concrete. This methodology provides a viable and sustainable strategy for integrating additive manufacturing with durable cementitious technologies, enabling the production of complex, resilient structures that combine ancient material logic with advanced digital fabrication. Since the millennial durability of the PEEK coating cannot be guaranteed, at least from a structural standpoint, it is more appropriate to rely on the weather resistance and self-healing properties of Roman concrete reinforced with small stainless steel reinforcements. The structural design should therefore neglect any contribution from the PEEK coating, treating it purely as non-structural. The formwork plays a crucial role in maintaining the integrity of the structure during the casting and curing phases of the cementitious material; however, its structural contribution is not considered in long-term design calculations, as its performance over centuries of service—despite potential maintenance—cannot be assured.

5 Distributed Additive Manufacturing System for Large-Scale Components

The patented 3D printing apparatus described by Piancastelli et al. [25] introduces a novel approach to large-scale additive manufacturing by employing a modular pseudo-matrix configuration composed of multiple compact 3D printers. Each module in this system is dedicated to fabricating a specific subcomponent of the final structure, enabling efficient, coordinated production of complex geometries. This work presents an innovative system architecture for additive manufacturing that employs a pseudo-matrix of interconnected 3D printing units to produce intricate, large-scale components. The configuration facilitates the distributed fabrication of discrete elements—analogous to puzzle pieces—which are subsequently assembled with high precision to reconstruct the target structure. The system is characterized by elevated design flexibility, modular scalability, and geometric adaptability, making it particularly suitable for industrial, prototyping, and customized manufacturing applications. The apparatus comprises a plurality of 3D printers arranged in a pseudo-matrix topology, each operating autonomously yet synchronously to produce modular sub-elements. These sub-elements are designed to integrate into the final assembly. The system's effective working area does not exceed the sum of the constituent printers' individual workspaces, thereby ensuring optimized resource allocation. The pseudo-matrix can be defined as an "n × m" grid, where each node corresponds to a discrete 3D printing unit interconnected via detachable couplings. This modular layout simplifies assembly, facilitates maintenance, and enables flexible system reconfiguration. The architecture supports both full-matrix configurations—suitable for continuous fabrication of flat or curved surfaces—and sparse-matrix configurations, in which units are selectively positioned to conform to the geometry of the object under construction, thereby maximizing spatial and operational efficiency. Notably, the pseudo-matrix can be deployed on both planar and curved surfaces. Moreover, the individual modules may be oriented with inclined working planes, enabling the system to produce components with complex cur curvilinear geometries, even when these geometries deviate from the global curvature of the support structure. The designation "pseudo-matrix" reflects the system's capacity for spatial deformation and dynamic reconfiguration along open or closed curved trajectories, further enhancing its geometric versatility and applicability in diverse production contexts. A particularly relevant application of this system is the construction of domes. In this case, each module is designed to simultaneously fabricate both an internal shell, which includes all necessary decorative elements, and an external shell, which plays a critical role in protecting the concrete structure from atmospheric agents. To ensure the mechanical integrity of the dome, the two

shells are connected by structural tie rods, as illustrated in Figure 2, which remain permanently integrated within the completed structure. This design solution guarantees cohesion between the internal and external surfaces throughout the entire dome, enhancing both durability and structural performance. The elements fabricated by the system form a set of interlocking parts that can be connected via a variety of mechanical coupling strategies. These include planar and three-dimensional interlocking joints, alignment pins, and auxiliary assembly tools such as geometric anchors or optical positioning devices. The integration methods among elements may include adhesive bonding, welding, brazing, mechanical fastening (e.g., nailing, riveting), or threaded connectors. Additionally, the fabrication sequence of the subcomponents can be optimized prior to printing, minimizing assembly time and reducing susceptibility to human error. This methodology represents a significant advancement in collaborative additive manufacturing, introducing a paradigm in which large-scale components are produced through the coordinated operation of mass-produced, small-scale printing units. The system thereby overcomes the dimensional limitations of individual printers and establishes a new framework for distributed modular design and fabrication.

6 Architectural Demonstrator: Parametric Dome Inspired by the Pantheon

To demonstrate the technical capabilities of the proposed system, a reference structure was designed, architecturally inspired by the Pantheon's dome in Rome. The external (upper) surface of the structure is a two-plane spherical segment, while the inner surface features a coffered geometry like that of the original Roman monument. The spherical surface (Figure 3) is subdivided into a triangular grid (triangulation), where each triangle (1) serves as a support plane for a single puzzle element composing the dome. Each of these elements is fabricated by an individual 3D printer (4). Each printer is programmed to manufacture a specific triangular portion of the two-plane spherical segment. The working planes (3) of the printers are inclined to match the slope of their corresponding triangles. The printhead (5) deposits material according to both the inclination of the plane and the required orientation of the part. Once printed, the triangular puzzle elements can be assembled progressively, ring by ring, until the dome is completed (Figure 3 and Figure 4). Each closed ring is self-supporting, ensuring structural stability without the need for external scaffolding. Alignment and orientation are ensured by geometric interlocks embedded into the printed elements, which function as reference features during assembly. Permanent joining of the segments can be achieved, for example, through structural adhesive bonding or welding.
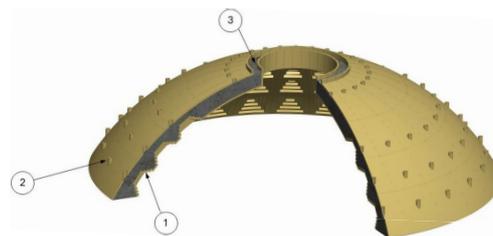

Figure 3. Partial sectional view of the dome and protective shell upon completion of construction

Note: (1) individual module featuring all required structural and aesthetic details; (2) access duct designed for the insertion of a concrete vibrator to eliminate air pockets; (3) upper casting duct intended for the pouring of concrete
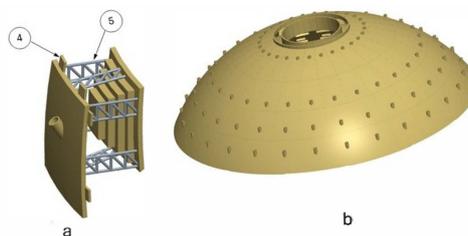

Figure 4. Single 3D-printed formwork module showing integrated functional features

Note: casting channels, vibration access points, mechanical interlocks, and reinforcement alignment guides are embedded during additive manufacturing. The permanent formwork ensures geometric control and environmental protection during curing and service. (a) view of a single printed module used to compose the shell. (4) interlocking features for proper alignment with adjacent modules; (5) integrated tie rods that ensure the preservation of geometric integrity. (b) fully assembled dome composed of all modular elements

7 Structural Analysis of the Parametric Dome

The structural behaviour of the dome is governed by its segmented ring configuration and the geometry of the individual puzzle elements. The assembly follows a ring-by-ring progression, where each completed ring acts as

a compression hoop that supports the subsequent layers. This self-supporting behaviour is analogous to classical masonry domes [26, 27]. Let the dome be idealized as a two-dimensional spherical shell with radius R. Let each horizontal ring be located at a vertical coordinate z measured upward from the springing (base) plane, with $0 \leq z \leq R$. For a spherical profile, the radius of the ring is $r(z) = \sqrt{(R^2 - z^2)}$. The equilibrium of a ring under self-weight can be modelled by considering the balance between vertical loading and the horizontal thrust generated at each interface. The hoop force resultant $H(z)$ at height z can be approximated as:

$$H(z) = \left(w \cdot R^2 \right) / \sqrt{\left(R^2 - z^2 \right)} \tag{1}$$

where, w is the weight per unit area, R is the radius of the dome, z is the vertical coordinate measured from the springing (base) plane.

As $z \to R$ (i.e., as $r(z) \to 0$ near the crown), $H(z)$ tends to infinity, indicating a rapid increase of hoop action in this idealized membrane model [27]. To ensure stability, the geometric interlocking of elements and the inclination of contact surfaces are designed to enforce compression-only behaviour. The dome assembly satisfies the condition:

$$\theta_c > \arctan(V/H) \tag{2}$$

where, θ_c is the contact inclination angle, V is the vertical load, and H is the horizontal thrust at a given ring. This condition ensures that no tensile forces are transmitted between puzzle elements. Numerical validation of the dome configuration was performed using finite element analysis (FEA) with nonlinear contact constraints, confirming its self-supporting behaviour within a defined tolerance. Similar simulation methodologies are presented in studies [28, 29]. Furthermore, structural joints were evaluated under worst-case loading conditions using bonded-contact assumptions. The bonding layer was modelled using cohesive zone modelling, assuming a fracture energy G_c of 250 J/m², consistent with typical structural adhesives [30]. This analysis confirms that the proposed modular design, when properly assembled, provides sufficient load-bearing capacity and geometrical stability for freestanding use, without the need for temporary scaffolding.

8   Coupled Polyether Ether Ketone-Slurry Modelling During Casting

Prior to the initial set, Roman concrete was modelled as a non-Newtonian slurry rather than as a solid continuum. In this early-age stage, the material exhibits negligible elastic stiffness and does not contribute to load-bearing capacity, transmitting stresses primarily through hydrostatic pressure and viscous shear. This behaviour is consistent with experimental observations on fresh cementitious suspensions and lime-based mortars [31, 32]. As a consequence, the structural response during casting is governed by the interaction between the fluid-like cementitious core and the confining permanent formwork. The adopted modelling framework is schematically illustrated in Figure 5. The permanent PEEK formwork (item 1 in the figure) is treated as a Lagrangian elastic shell and represents the sole load-bearing component during casting. The fresh Roman concrete (item 2) is modelled as a yield-stress slurry occupying the internal cavity, with a free surface that rises progressively with the casting rate (item 3). This representation allows large deformations and free-surface evolution to be captured while avoiding the attribution of artificial stiffness to the cementitious matrix. The slurry was represented using a Herschel-Bulkley yield-stress fluid model, with its parameters treated as time-dependent to account for the slow onset of setting characteristic of opus caementicium [33]. The fresh concrete domain was treated using a Eulerian or Smoothed Particle Hydrodynamics formulation within ANSYS Explicit Dynamics, enabling a physically consistent description of flow, pressure redistribution, and interaction with the deformable formwork during casting. During slow casting, the dominant load acting on the formwork is hydrostatic pressure generated by the rising slurry level. As indicated in Figure 5 (item 4), this pressure varies with depth and time, depending on the filling height, and an additional viscous contribution arises from the non-Newtonian rheology of the mixture. Accordingly, pressure-time histories were applied to the formwork's internal surfaces, with the filling height varying with the imposed casting rate. Time-dependent increases in yield stress and consistency (item 5) were introduced to represent the progressive loss of fluidity during early curing, while still excluding any elastic or plastic resistance contribution from the cementitious core. A Drucker–Prager plasticity model was intentionally not adopted for the fresh mixture. Such formulations are intended for solid granular materials and do not capture shear-rate-dependent behaviour. Their use in the present context would introduce nonphysical arching effects and solid-like stress transfer, leading to an underestimation of lateral pressures acting on the formwork during casting and compromising the conservativeness of the analysis. Because of this coupled PEEK-slurry representation, the subsequent numerical analyses focus on the structural verification of the permanent formwork under post-casting conditions. In particular, once the cavity is fully filled and the slurry level has reached its final height, the formwork is subjected to sustained hydrostatic loading prior to any significant strength development of the Roman concrete. The following subsection therefore introduces the finite element analysis performed under hydrostatic pressure after casting, which represents the governing load case for the system's early-age structural safety.
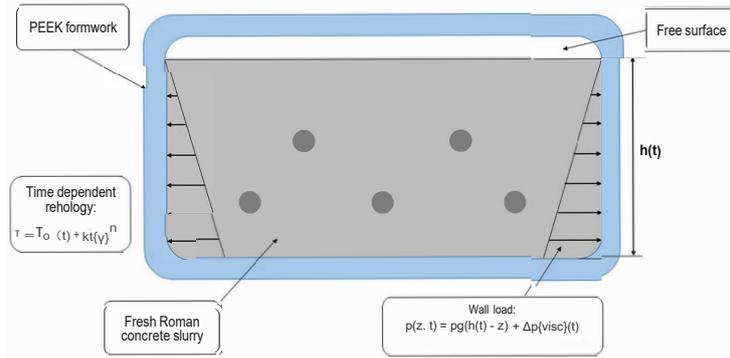
Figure 5. Clean conceptual scheme of the coupled polyether ether ketone (PEEK)-slurry model during casting

8.1 Finite Element Analysis Framework for Post-Casting Hydrostatic Loading

The finite element analysis presented in this section is aimed at verifying the structural behaviour of the permanent PEEK formwork under post-casting conditions, which represent the governing load case during the early-age phase of Roman concrete. Once the cavity is fully filled and the slurry level has reached its final height, the cementitious matrix has not yet developed significant mechanical stiffness and therefore cannot be considered load-bearing. In this configuration, the formwork is subjected to sustained hydrostatic pressure generated by the fresh concrete, as schematically illustrated in Figure 5. The numerical investigation is intentionally focused on the post-casting stage rather than on the transient filling process. While pressure evolution during casting is relevant for constructability assessment, the maximum and most persistent demand on the formwork occurs after casting is complete, when hydrostatic loading acts continuously over extended time intervals prior to the onset of significant setting and strength development. This condition is therefore identified as the critical scenario for early-age structural safety. In the adopted finite element framework, the permanent formwork is modelled as the sole load-bearing structural component. The Roman concrete core is represented exclusively through its mass density and hydrostatic action, without assigning elastic or plastic resistance. This modelling choice ensures a conservative assessment by avoiding any artificial contribution from the cementitious matrix before it becomes mechanically effective. Hydrostatic pressure is applied to the internal surfaces of the formwork as a depth-dependent load that increases linearly from the free surface to the cavity base. The pressure distribution follows the classical formulation:

$$p(z) = \rho \cdot g \cdot (H - z) \tag{3}$$

where, ρ is the density of the fresh mixture, g is gravitational acceleration, H is the final filling height, and z is the vertical coordinate measured from the base. No reduction due to arching, internal friction, or solid-like stress transfer is observed, consistent with the material's fluid-dominated behaviour at this stage. The objective of the analysis is to verify that stresses and deformations induced in the permanent formwork by sustained hydrostatic loading remain within admissible limits throughout the early curing period. The results provide a quantitative basis for assessing whether the formwork can safely sustain the most demanding early-age condition until the Roman concrete progressively transitions from a non-structural filler to a load-bearing material in subsequent stages of curing. Table 3 summarizes the material models and properties adopted in the finite element analysis. The PEEK formwork is modelled as a linear elastic material, consistent with its role as the sole load-bearing component during early-age conditions. The fresh Roman concrete is introduced only through its density and hydrostatic action, with no elastic or plastic parameters assigned, reflecting its slurry-like behaviour prior to initial set.

Table 3. Material models and properties adopted in the finite element analysis for the post-casting stage

Component	Model	Density [kg/m^3]	Elastic Properties
Polyether ether ketone (PEEK) formwork	Linear elastic	1300	$E = 4.0$ GPa, $\nu = 0.38$
Roman concrete (fresh)	Fluid-like load	1800	-

8.2 Finite Element Analysis Simulation of the Pre-Casting Hydrostatic Pressure Stage

A finite element simulation was performed to evaluate the structural response of the permanent PEEK formwork during the pre-casting stage, when the Roman concrete is fully fluid and provides no mechanical contribution. In this configuration, the thermoplastic formwork serves as the sole load-bearing system, while the cementitious material acts solely as a hydrostatic load. The numerical model reproduces the segmented dome geometry inspired by the

Pantheon configuration (Figure 6), including the oculus opening and the modular subdivision of the formwork. The PEEK shell was modelled as a linear elastic solid, whereas the internal volume was treated as a liquid domain, with its effect accounted for by a depth-dependent hydrostatic pressure acting on the inner surfaces of the formwork. No stiffness, strength, or confinement contribution was assigned to the concrete at this stage. This loading condition represents the most unfavourable early-age scenario, as the pressure acts continuously on the formwork prior to any setting or strength development of the cementitious matrix. Figure 6 shows the resulting stress distribution in the PEEK formwork under pre-casting hydrostatic pressure. The stress field is smoothly distributed over the shell, with maximum values localized around geometric discontinuities such as the oculus region and changes in curvature, while lower stresses are observed toward the base of the dome. This behaviour is consistent with shell theory and confirms that the structural demand during the pre-casting phase is governed by geometry and hydrostatic loading rather than by the mechanical properties of the cementitious core. The results demonstrate that, under the assumed loading conditions, the permanent formwork can sustain the pre-casting hydrostatic pressure without structural instability, thereby providing a safe containment system during the most critical early-age phase of construction.
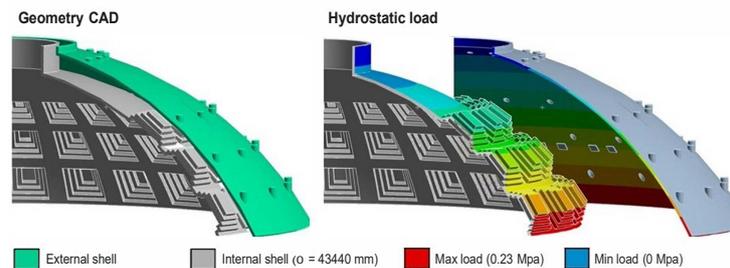

Figure 6. CAD model of the Pantheon dome formwork used in the numerical simulation

Note: geometric representation of the dome framework highlighting the structural configuration of the permanent formwork (left); von Mises stress distribution in the formwork induced by hydrostatic pressure from the fluid concrete during casting, showing stress concentrations near the base and smooth stress gradients along the dome surface (right)

9   Cost Effectiveness

Although Roman structures were highly expensive to construct, many of them—such as aqueducts, bridges, the Cloaca Maxima, and the Pantheon—are still in use today. Their extraordinary durability and minimal maintenance requirements have resulted in an exceptionally low annualized cost over millennia. These constructions demonstrate that a high initial investment can be justified when long-term performance and durability are prioritized. Similarly, a modern structural system employing PEEK formworks and Roman concrete, with internal reinforcement also made of PEEK, may entail high upfront costs. Furthermore, such a structure may not be immediately accessible or operational due to curing and consolidation requirements. However, if designed for longevity and minimal maintenance, its lifecycle cost could be significantly lower than conventional solutions, reflecting the same long-term cost-effectiveness observed in ancient Roman infrastructure. In other words, a modern structure built with PEEK formworks and Roman concrete—though initially expensive and not immediately usable—could achieve long-term cost-effectiveness through exceptional durability and reduced maintenance needs, much like ancient Roman infrastructure.

10   Validation of the Proposed System

The distributed additive manufacturing system successfully produced self-supporting formwork modules with dimensional deviations below the adopted tolerance threshold. Assembly tests confirmed geometric continuity and alignment consistency across modular interfaces. The permanent formwork sustained hydrostatic casting pressures without structural instability. Observed elastic deformation remained within predicted ranges and did not compromise the final geometry after curing. The formwork accommodated prolonged curing periods without degradation or loss of containment. No evidence of incompatibility between the thermoplastic shell and the cementitious matrix was observed. The integrated system reduced direct exposure of the concrete to the environment, eliminated the need for secondary protective coatings, and minimized corrosion-prone interfaces. These factors collectively satisfy the necessary conditions for extended service life. The segmented dome confirmed the feasibility of scaling the proposed system to complex geometries. Assembly sequencing, self-supporting behaviour, and functional integration validated the system-level design assumptions.

11 Discussion

11.1 System-Level Interpretation of Durability

The results presented in this study should be interpreted within a system-level framework rather than as isolated material or component performances. The primary contribution of the proposed approach lies in demonstrating that durability can be embedded as a governing design objective through the coherent integration of cementitious chemistry, reinforcement strategy, and fabrication method. Unlike conventional reinforced concrete systems, in which durability relies on secondary protective measures applied after casting, the proposed system incorporates protection, containment, and geometric control directly into the construction logic. It is important to emphasize that the enhanced durability observed in the results does not result from a single material innovation, but rather from the alignment of multiple necessary conditions for long-term performance. The slow hydration and self-healing behaviour of Roman concrete, the corrosion resistance of stainless steel reinforcement, and the environmental shielding provided by the permanent formwork collectively suppress the dominant degradation mechanisms observed in modern reinforced concrete structures. The research questions addressed in this study and the corresponding validation criteria are summarized in Table 4.

Table 4. Research questions addressed in the study and corresponding validation criteria and assessment methods for the proposed additive-manufactured permanent formwork system

Research Question	Validation Criteria	Method of Assessment
Can large-format additive manufacturing produce self-supporting formworks suitable for slow-curing concrete?	Geometric accuracy, dimensional stability, load-bearing capacity during casting	Dimensional measurements, assembly tests, analytical load evaluation
Is the permanent formwork compatible with the casting and curing behaviour of Roman concrete?	Formwork deformation, shrinkage accommodation, preservation of final geometry	Qualitative observation, analytical comparison, curing-stage assessment
Does the integrated system support durability-oriented design objectives?	Reduction of exposed concrete surfaces, elimination of secondary coatings, mitigation of corrosion-prone interfaces	System-level analysis, material compatibility evaluation, literature-based durability proxies
Is the proposed approach scalable to architectural components?	Constructability, assembly logic, geometric continuity at component scale	Full design of a demonstrator fabrication and finite element analysis (FEA) evaluation

11.2 Validity and Limitations of Proxy Durability Metrics

A foreseeable concern in evaluating this work is the lack of direct, long-term durability data. Given the century or millennial-scale timeframes associated with Roman concrete, such validation is inherently impractical within laboratory or project-based research. For this reason, the study adopts proxy metrics widely accepted in durability science, focusing on verifying necessary conditions rather than predicting exact service life. These proxy metrics include chemical compatibility between materials, mechanical compatibility during curing, and reduced exposure pathways that contribute to environmental degradation. While these criteria cannot provide absolute lifetime predictions, they enable a scientifically grounded assessment of whether the proposed system is structurally and chemically predisposed toward long-term durability. This approach is consistent with established methodologies in materials aging, corrosion science, and heritage conservation research.

11.3 Role of Permanent Formwork as a Durability Component

One of the key conceptual shifts introduced by this work is the redefinition of formwork from a temporary construction aid to a permanent component of the durability strategy. The results demonstrate that additive manufacturing enables the fabrication of formworks that are not only geometrically precise but also capable of accommodating the extended curing behaviour of slow-reacting cementitious systems. The permanent formwork provides multiple functions: containment during casting, elastic accommodation of deformation, and long-term environmental shielding. Although the formwork is intentionally excluded from long-term structural load calculations due to uncertainties associated with polymer aging, its contribution to durability through exposure reduction remains significant. This distinction between structural and protective roles is essential to avoid overestimating the long-term mechanical contribution of polymeric components.

11.4 Scalability and Generalizability of the Proposed Framework

The architectural-scale demonstrator presented in this study is not intended as a one-off prototype, but as a validation of scalability and constructability. The segmented dome confirms that the proposed system can be extended to complex geometries and assembled through modular fabrication without reliance on temporary scaffolding or disposable formworks. While the case study draws inspiration from Roman precedents, the underlying framework is not limited to Roman concrete formulations. The principles developed here are applicable to a broader class of slow-curing or alternative cementitious materials, including lime-based, geopolymeric, or low-clinker systems, provided that material compatibility and curing behaviour are appropriately considered. In this sense, the work contributes a generalizable construction paradigm rather than a material-specific solution.

11.5 Implications for Contemporary Construction Practice

From a practical standpoint, the proposed system challenges prevailing construction paradigms that prioritize early-age strength, rapid turnover, and short-term cost optimization. While such paradigms are well-suited to high-throughput construction, they are misaligned with applications requiring extended service life and minimal intervention. The adoption of durability-driven construction systems inevitably entails trade-offs, including longer curing periods, higher initial material costs, and increased design complexity. However, when evaluated over lifecycle horizons, these trade-offs may be offset by reduced maintenance, extended service life, and improved resilience. The results of this study provide a conceptual and technical basis for evaluating such trade-offs within a scientifically grounded framework.

11.6 Limitations and Future Research Directions

Several limitations of the present study should be acknowledged. First, while material compatibility and early-age behaviour are addressed, long-term environmental aging of the thermoplastic formwork remains an open research question. Accelerated aging studies under controlled exposure conditions represent a logical next step to refine the protective role of permanent formworks. Second, structural validation is limited to architectural component scale and analytical modelling. Full-scale structural testing under service and extreme loading conditions would further strengthen the framework, particularly for applications beyond compression-dominated geometries. Finally, future research should investigate optimization strategies for material usage, printing parameters, and formwork topology to balance durability, manufacturability, and sustainability. Such studies would enable the translation of the proposed framework from experimental demonstrators to standardized construction systems. Overall, this work establishes a durability-driven research direction that bridges ancient material knowledge and contemporary additive manufacturing. Rather than offering definitive lifetime predictions, it provides a verifiable and generalizable framework for designing construction systems oriented toward extended service life, addressing a critical and enduring challenge in the built environment.

12 Conclusions

This study has presented a durability-driven construction framework that integrates Roman-type concrete, stainless steel reinforcement, and permanent additively manufactured thermoplastic formworks into a coherent material–process system. Rather than pursuing incremental improvements to conventional reinforced concrete, the proposed approach reframes durability as a primary design objective emerging from the interaction between material chemistry, reinforcement strategy, and fabrication logic. A key contribution of the work lies in the redefinition of formwork. Instead of acting as a temporary construction aid, the formwork is conceived as a permanent protective enclosure that provides geometric control during casting, sustains early-age loads, accommodates the slow curing behaviour of Roman concrete, and reduces long-term environmental exposure. Importantly, the structural contribution of the thermoplastic formwork is intentionally excluded from long-term design calculations, ensuring that load-bearing capacity is conservatively governed by the cementitious matrix and reinforcement once maturation is complete. The early-age structural behaviour of the system was investigated through finite element analysis, focusing on the most critical construction stages. Both pre-casting and post-casting configurations were examined by modelling the fresh Roman concrete as a fluid-like load acting on the permanent formwork. These analyses demonstrate that the governing demand during early-age conditions is driven by hydrostatic pressure and geometry, and that the formwork can sustain these loads without structural instability prior to concrete setting. This validation is essential for enabling the use of slow-curing, high-durability binders within modern construction workflows. An architectural-scale demonstrator inspired by the Pantheon was employed to assess constructability, modularity, and scalability. The segmented dome confirms that the proposed system can be extended to complex geometries and assembled through distributed additive manufacturing without reliance on temporary scaffolding or disposable formworks. While the demonstrator does not constitute proof of long-term durability, it provides verifiable evidence that the system meets the necessary conditions for extended service life, as defined by current materials science and structural engineering knowledge. Several limitations must be acknowledged. Long-term mechanical performance

of thermoplastic formworks under environmental aging cannot be guaranteed over century-scale horizons and was therefore conservatively neglected in structural design. In addition, validation is limited to analytical modelling and to the scale of architectural components. Full-scale testing and accelerated aging studies are required to further quantify long-term behaviour and refine protective assumptions. Overall, the proposed framework establishes a scientifically grounded pathway for integrating ancient durability principles with contemporary additive manufacturing and computational analysis. By explicitly separating early-age support from long-term load-bearing behaviour and embedding durability at the system level, this work contributes an alternative to maintenance-driven construction paradigms and provides a foundation for future research on long-life infrastructure and durability-oriented design.

Author Contributions

Conceptualization, L.P. and A.M.; methodology, L.P. and A.M.; software, A.M. and G.M.S.; validation, L.P.; formal analysis, L.P.; investigation, L.P. and G.M.S.; resources, L.P., A.M. and G.M.S.; data curation, G.M.S.; writing—original draft preparation, L.P. and A.M.; writing—review and editing, L.P. and A.M.; visualization, A.M.; supervision, L.P.; project administration, L.P.; funding acquisition, L.P. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] L. Piancastelli and E. Lorenzini, "Evolving durability strategies in concrete structures from the Roman era to today," *J. Civ. Hydraul. Eng.*, vol. 3, no. 2, pp. 113–123, 2025. https://doi.org/10.56578/jche030205

[2] L. Piancastelli and E. Lorenzini, "Innovating modern cement by harnessing solutions from ancient Roman concrete," *J. Civ. Hydraul. Eng.*, vol. 3, no. 3, pp. 151–158, 2025. https://doi.org/10.56578/jche030303

[3] 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

[4] I. Gibson, D. Rosen, and B. Stucker, *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, 2nd ed. New York: Springer, 2015. https://doi.org/10.1007/978-1-4939-2113-3

[5] S. Wickramasinghe, T. Do, and P. Tran, "FDM-based 3D printing of polymer and associated composite: A review on mechanical properties, defects and treatments," *Polymers*, vol. 12, no. 7, p. 1529, 2020. https://doi.org/10.3390/polym12071529

[6] M. Heskin, B. Deuser, T. Schuman, K. Chandrashekhara, J. Bayldon, J. DeGrange, S. Patterson, and N. Levenhagen, "Mechanical and thermal characterization of additively manufactured carbon/nylon 12 and carbon/PEEK composites," *Appl. Compos. Mater.*, vol. 32, pp. 2789–2809, 2025. https://doi.org/10.1007/s10443-025-10363-z

[7] Y. Wang, W. D. Müller, A. Rumjahn, F. Schmidt, and A. D. Schwitalla, "Mechanical properties of fused filament fabricated PEEK for biomedical applications depending on additive manufacturing parameters," *J. Mech. Behav. Biomed. Mater.*, vol. 115, p. 104250, 2021. https://doi.org/10.1016/j.jmbbm.2020.104250

[8] M. Adamson and B. Eslami, "Post-processing PEEK 3D-printed parts: Experimental investigation of annealing on microscale and macroscale properties," *Polymers (Basel)*, vol. 17, no. 6, p. 744, 2025. https://doi.org/10.3390/polym17060744

[9] A. Diouf Lewis, R. D. Farahani, F. Iervolino, J. Pierre, Y. Abderrafai, M. Lévesque, N. Piccirelli, and D. Therriault, "Design and characterization of carbon fiber-reinforced PEEK/PEI blends for fused filament fabrication additive manufacturing," *Mater. Today Commun.*, vol. 31, p. 103445, 2022. https://doi.org/10.1016/j.mtcomm.2022.103445

[10] K. D. D. Martínez-López, J. d. J. Kú-Herrera, G. Morales, J. M. Cervantes-Uc, A. May-Pat, and D. M. Ramírez-López, "Optimizing interlayer adhesion of FFF-printed PEEK on an accessible platform via short-beam shear testing and response surface methodology," *Mater. Today Commun.*, vol. 49, p. 114076, 2025. https://doi.org/10.1016/j.mtcomm.2025.114076

[11] Victrex plc, "Materials properties guide—PEEK," Technical Datasheet, 2012. https://www.victrex.com/en/material-properties

[12] Solvay Specialty Polymers, "Ketaspire PEEK: Shelf life and accelerated ageing study," Technical Report, 2016. https://www.solvay.com/sites/g/files/srpend616/files/2018-07/ketaspire-peek-shelflife-sterilization-en.pdf

[13] S. J. Ferguson, J. M. A. Visser, and A. Polikeit, "The long-term mechanical integrity of non-reinforced PEEK-OPTIMA polymer for demanding spinal applications: Experimental and finite-element analysis," *Eur Spine J*, vol. 15, pp. 149–156, 2006. https://doi.org/10.1007/s00586-005-0915-5

[14] J. Ahmad and M. G. Niasar, "Aging behavior of PEEK, PTFE, and PI insulation materials under thermal oxidative and humid conditions for aerospace applications," *J. Appl. Polym. Sci.*, vol. 142, no. 19, p. e56858, 2025. https://doi.org/10.1002/app.56858

[15] M. Frigione and A. Rodríguez-Prieto, "Can accelerated aging procedures predict the long term behavior of polymers exposed to different environments?" *Polymers*, vol. 13, no. 16, p. 2688, 2021. https://doi.org/10.3390/polym13162688

[16] R. Ding, L. Xu, J. Li, J. Liao, J. Wang, Z. Wang, and H. Ma, "Investigation and life expectancy prediction on poly (ether-ether-ketone) cables for thermo-oxidative aging in containment dome of nuclear power plant," *Polym. Test.*, vol. 103, p. 107362, 2021. https://doi.org/10.1016/j.polymertesting.2021.107362

[17] N. T. Chinh and T. Hoang, "Life-time prediction for polymer materials," *Vietnam J. Sci. Technol.*, vol. 59, no. 5, pp. 527–551, 2021. https://doi.org/10.15625/2525-2518/59/5/16057

[18] S. M. Kurtz, *PEEK Biomaterials Handbook.* Oxford: William Andrew/Elsevier, 2012. https://doi.org/10.1016/C2010-0-66334-6

[19] P. Sundriyal, M. Sahu, O. Prakash, and S. Bhattacharya, "Long-term surface modification of PEEK polymer using plasma and PEG silane treatment," *Surf. Interfaces*, vol. 25, p. 101253, 2021. https://doi.org/10.1016/j.surfin.2021.101253

[20] B. Xie, C. Jiang, Y. Li, I. Cotton, and D. A. Hall, "Aerosol deposition of alumina ceramic coatings on polyether ether ketone (PEEK) for high-voltage insulation," *J. Mater. Res. Technol.*, vol. 38, pp. 4688–4697, 2025. https://doi.org/10.1016/j.jmrt.2025.08.119

[21] B. Ortega-Bautista, J. Henao, C. A. Poblano-Salas, A. L. Giraldo-Betancur, D. Espinosa-Arbelaez, J. Corona-Castuera, O. Sotelo-Mazón, and J. M. Gonzalez-Carmona, "Understanding the deposition of multilayered hydroxyapatite-bioactive glass/hydroxyapatite/titanium dioxide coatings on PEEK substrates by plasma spray," *Surf. Coat. Technol.*, vol. 494, no. Part 3, p. 131543, 2024. https://doi.org/10.1016/j.surfcoat.2024.131543

[22] A. Nandi, A. K. Biswal, A. Nguyen, L. Nordyke, E. Behling, T. Foulds, K. Schultz, and A. Vashisth, "Comparative study of surface preparation for paint adhesion on CF-PEKK composites: Plasma, chemical, and flame treatment," *Appl. Surf. Sci.*, vol. 669, p. 160533, 2024. https://doi.org/10.1016/j.apsusc.2024.160533

[23] S. J. Park, J. E. Lee, J. Park, N. K. Lee, Y. Son, and S. H. Park, "High-temperature 3D printing of polyetheretherketone products: Perspective on industrial manufacturing applications of super engineering plastics," *Mater. Des.*, vol. 211, p. 110163, 2021. https://doi.org/10.1016/j.matdes.2021.110163

[24] T. Hanemann, A. Klein, S. Baumgärtner, J. Jung, D. Wilhelm, and S. Antusch, "Material extrusion 3D printing of PEEK-based composites," *Polymers*, vol. 15, no. 16, p. 3412, 2023. https://doi.org/10.3390/polym15163412

[25] L. Piancastelli, A. Montalti, and G. M. Santi, "Modular apparatus for the three-dimensional printing of large-scale structures," Italian Utility Model Patent Application 202 025 000 002 359, 2025. https://servizionline.uibm.gov.it/deposito-online-new/pubblica/index.html

[26] R. Maia Avelino, A. Iannuzzo, T. Van Mele, and P. Block, "Assessing the safety of vaulted masonry structures using thrust network analysis," *Comput. Struct.*, vol. 257, p. 106647, 2021. https://doi.org/10.1016/j.compstruc.2021.106647

[27] P. Block, "Thrust network analysis: Exploring three-dimensional equilibrium," Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, MA, USA, 2007. http://hdl.handle.net/1721.1/49539

[28] M. Rippmann, L. Lachauer, and P. Block, "Interactive vault design," *Int. J. Space Struct.*, vol. 27, no. 4, pp. 219–230, 2012. https://doi.org/10.1260/0266-3511.27.4.219

[29] S. Adriaenssens, P. Block, D. Veenendaal, and C. Williams, *Shell Structures for Architecture: Form Finding and Optimization*, 1st ed. London: Routledge, 2014. https://doi.org/10.4324/9781315849270

[30] L. F. M. Da Silva, A. Oechsner, and R. D. Adams, *Handbook of Adhesion Technology.* Berlin, Germany: Springer, 2006. https://doi.org/10.1007/978-3-642-01169-6_1

[31] N. Roussel, "A thixotropy model for fresh fluid concretes: Theory, validation and applications," *Cem. Concr. Res.*, vol. 36, pp. 1797–1806, 2006. https://doi.org/10.1016/j.cemconres.2006.05.025

[32] A. Sharma, S. Gupta, M. Noman Husain, and S. Chaudhary, "Factors affecting the rheology of cement-based composites: A review," *J. Am. Ceram. Soc.*, vol. 108, p. e20429, 2025. https://doi.org/10.1111/jace.20429

[33] F. J. Sohounme, M. Neji, N. Seigneur, K. Schörle, A. Coutelas, T. Charpentier, M. Moskura, C. Jardin, and A. Dauzères, "Hydration mechanisms in Roman seawater concrete: Archaeological analogue for validation of long-term ageing reactive transport model," *Cem. Concr. Res.*, vol. 201, p. 108114, 2026. https://doi.org/10.1016/j.cemconres.2025.108114