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Research Article

A Comprehensive Review on 3D-Printed Cement-Based Lattice Structures

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Keywords

3D printing in civil engineering cementitious composites, Cement-based 3D lattice structures, Eco-friendly construction technologies, Sustainable construction.

Abstract

This investigation examines the potential of 3D-printed cement-based lattice structures as a revolutionary approach for sustainable construction methodologies. By utilizing additive manufacturing technologies, this research confronts significant drawbacks inherent in conventional cementitious materials, such as inadequate tensile strength and brittleness, through the incorporation of advanced lattice geometries. Principal findings indicate that lattice structures markedly improve material efficiency, decrease weight, and enhance mechanical performance, including increased ductility and durability. The study elucidates how these structures promote optimized stress distribution, thereby delaying crack propagation and ensuring enduring structural integrity when subjected to environmental effects such as cyclical loading, temperature variations, and moisture exposure. Furthermore, the research emphasizes the sustainability of 3D-printed lattice structures, highlighting reduced cement consumption and a diminished carbon footprint. The versatility of this methodology facilitates the production of lightweight, high-performance building elements that are well-suited for applications in resilient infrastructure, energy-efficient design, and disaster recovery initiatives. This pioneering approach not only propels material optimization and structural resilience but also aligns with global sustainability objectives, representing a significant advancement in the progression of construction technologies. These findings establish a basis for further investigation of scalable 3D printing applications and act as a guide for engineers and policymakers aiming to enhance material efficiency and sustainability in the construction sector.

1. Introduction and Overview of 3D-Printed Lattice Structures

In recent years, the adoption of digitalized construction methodologies in civil engineering has gained significant traction, with additive manufacturing (commonly known as 3D printing) emerging as a transformative technology for fabricating cement-based materials [1-3]. A key limitation of traditional cement-based materials is their low tensile strength and susceptibility to cracking, stemming from inadequate ductility [4]. While steel reinforcements have been utilized to improve these properties, issues such as corrosion remain a major durability concern, potentially compromising structural integrity over time [5, 6].

The advent of 3D-printing technology offers significant potential to address these challenges through its ability to create intricate geometries and enhance the structural performance of cementitious materials. Lattice structures produced via 3D printing, characterized by an interconnected arrangement of voids, have demonstrated superior mechanical and material efficiency properties [7]. This adaptability allows for the customization of lattice designs, including unit cell dimensions and geometrical configurations, to optimize tensile strength, rigidity, and ductility, meeting specific structural requirements [8-10]. Furthermore, lattice structures improve material efficiency by reducing overall weight while retaining load-bearing capacity [11]. Their intrinsic porosity enhances stress distribution, minimizing crack propagation and ensuring long-term structural integrity under diverse environmental conditions, including repeated loading, temperature fluctuations, and moisture exposure [3]. These attributes make 3D-printed cementitious lattice structures particularly valuable for sustainable construction by reducing material usage, transportation costs, and the ecological footprint of construction activities [12].

The use of lattice reinforcement also mitigates traditional limitations of cement-based composites, such as brittleness and localized stress concentrations, by redistributing external loads through a network of interconnected struts and nodes [13, 14]. This approach extends the operational lifespan of structural components and reduces lifecycle costs associated with maintenance and repairs [15]. This review aims to synthesize contemporary advancements in 3D-printed lattice structures, focusing on their potential to revolutionize construction methodologies by enhancing material performance and promoting sustainability. It provides a comprehensive framework for academic researchers, practicing engineers, and policymakers, highlighting the practical applications of these innovations and their alignment with global sustainability objectives. By systematically evaluating existing research, this review identifies optimal solutions for improving the performance and durability of cement-based composites, laying the groundwork for resilient and resource-efficient infrastructure rehabilitation [16-19].

Although research on 3D-printed cement-based structures is extensive, studies on lattice-based systems are limited and lack the synthesis of their mechanical and sustainability features. This paper presents the first comprehensive review of 3D-printed cement-based lattice structures. In contrast to prior studies that focused on singular aspects or specific geometries, this review consolidates various findings into a cohesive

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framework. By critically assessing the lattice configurations and their efficiencies, this study serves as a foundational reference for subsequent studies and practical applications.

2. Lattice Structures

3D-printing, commonly known as additive manufacturing, has emerged as a transformative technology within the construction sector, enabling the creation of complex geometries directly from digital designs [20-23]. Techniques such as Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Stereolithography (SLA) are widely employed, each offering unique capabilities. FDM uses thermoplastic filaments for large-scale constructs, SLS employs lasers to fuse powdered substances into robust components, and SLA solidifies liquid resin to achieve high-resolution outputs [24-26]. Additional methodologies, including Binder Jetting and Concrete Extrusion Printing (CEP), further expand the fabrication potential for bespoke and large-scale construction components [27]. The advantages of 3D printing include expedited prototyping, reduced material waste, on-site manufacturing, and enhanced design adaptability, fostering architectural innovation and sustainability [28]. However, challenges such as scalability for large projects, material optimization, compliance with regulations, and addressing environmental concerns require ongoing research and development to fully realize the transformative potential of this technology in construction and infrastructure advancement.

3D-printed cement-based polymer lattice structures have shown significant promise in improving the mechanical properties of concrete [29, 30]. These frameworks, typically fabricated through FDM using materials like acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), offer advantages such as reduced weight, enhanced corrosion resistance, and thermal insulation [31-33]. Research demonstrates that integrating 3D-printed polymer reinforcements significantly enhances the ductility of cementitious materials [15]. This is attributed to the innovative structural benefits of cement-based lattice designs, which combine weight reduction, strength amplification, and material efficiency. Cement-based 3D-printed lattice structures, distinguished by a network of interconnected voids within a cementitious matrix, aim to enhance material efficiency while maintaining or improving structural integrity [33, 34]. These structures are categorized based on geometric configurations and applications [35]. Regular lattices feature uniform unit cells arranged systematically, offering predictable mechanical properties [36, 37]. Irregular lattices provide flexibility through nonuniform unit cells, enabling customization for applications with varying structural requirements [38]. Hierarchical lattice architectures incorporate multiple layers of complexity, optimizing performance across scales and addressing diverse stress conditions [35, 39, 40].

The design of lattice structures incorporates several principles to maximize structural efficiency and material utilization. Unit cell morphology, dimensions, and alignment are critical in determining mechanical properties such as tensile strength and load-bearing capacity [34, 41]. Material selection, including cementitious compositions and admixtures like fibers or nanoparticles, significantly impacts performance and durability [42-45]. Topology optimization reduces material consumption while enhancing performance through effective load distribution and stress management [29, 33, 46]. Production techniques, such as layer-wise deposition in 3D printing or traditional casting, determine the final geometry and integrity of the lattice structure. Cement-based lattice structures deliver significant benefits, including weight reduction, strength-to-weight ratio improvement, and enhanced mechanical performance [33, 37, 47]. Their porosity minimizes material usage and promotes sustainability by reducing costs and environmental impacts [3]. Additionally, the interconnected voids enhance stress distribution, reducing crack propagation and improving durability, leading to lower maintenance demands and lifecycle costs [34].

3. A Brief Review of Current Literature on 3D Printed Lattice Structures

Innovative technologies frequently challenge the traditional methodologies in the field of construction. Among these advancements, 3D printed cement-based lattice structures stand out as a revolutionary development, despite their relatively scarce representation in the scholarly literature. Concrete, recognized for its remarkable compressive strength, faces intrinsic limitations, such as susceptibility to brittleness in tension and insufficient crack resistance. The integration of polymeric lattices fabricated through techniques such as Polylactic Acid (PLA) or Acrylonitrile Butadiene Styrene (ABS) in 3D printing offers a promising strategy for enhancing the mechanical properties of cement-based materials [48].

Despite their promise, academic inquiry into this innovative methodology remains conspicuously constrained. This review, which represents the inaugural review addressing only 3D-printed cement-based lattice structures, addresses this deficiency by meticulously scrutinizing the extant body of knowledge on 3D printed cement-based lattice configurations. As the first exhaustive compilation of its kind, this review elucidates the transformative potential of these technologies in the construction industry. By aggregating disparate insights, this review functions as a foundational reference for scholars, engineers, and industry practitioners to explore and enhance the applications of these avant-garde structural paradigms. Moreover, this review not only synthesizes a limited yet impactful array of information sources but also establishes a structure for future investigations and practical applications in the domain. It emphasizes the strategic significance of evolving structural engineering techniques and promoting sustainable construction practices. By revealing unexplored pathways, this review article seeks to stimulate discourse and innovation, which will shape the future trajectory of construction methodologies.

In recent years, 3D printing technologies have emerged as a pioneering tool to enhance the mechanical, thermal, and functional properties of cement-based composites. Studies in this domain demonstrate the potential of polymer lattice structures to improve material performance and structural enhancements. Song et al. (2021) [49] (Figure1) explored lattice structures produced through stereolithography (SLA), showing their effectiveness in lightweight construction applications by optimizing both mechanical strength and thermal resistance. These structures exhibited low thermal conductivity and increased flexibility due to multi-crack damage mechanisms. Wan et al. (2022) [50] (Figure 2) investigated 3D-printed vascular networks, highlighting their ability to enhance self-healing properties and ensure complete water tightness, significantly extending concrete durability. Similarly, Song et al. (2021) [51] (Figure 3) emphasized how polymer-supported lattice structures enhanced deformation capacity and durability in lightweight construction materials. Salazar et al. (2020) [15] (Figure 4) demonstrated that polymer lattice structures were a promising alternative for ultra-high-performance concrete (UHPC), transforming its behavior to exhibit multiple cracking under stress. Xu et al. (2021) [52] (Figure 5) found that functionally graded lattice structures increased flexural capacity while reducing reinforcement ratios. Liu et al. (2022) [53] (Figure 6) analyzed the stress distribution facilitated by 3D-printed lattices, revealing improved load-bearing capacity and reduced brittleness.

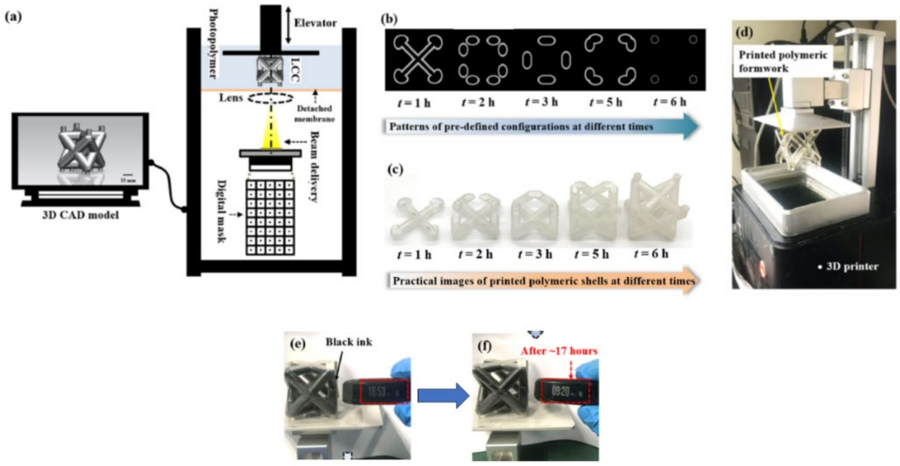

Figure 1. (a) A diagrammatic representation of the printing methodology. (b) Cross-sectional images depicting the printing configurations at various temporal intervals. (c) FCC-PFs that have been printed and subsequently halted at distinct time points. (d) Visual representations of the printed FCC-PS. (e–f) Assessment of the structural integrity of FCC-PF [49]

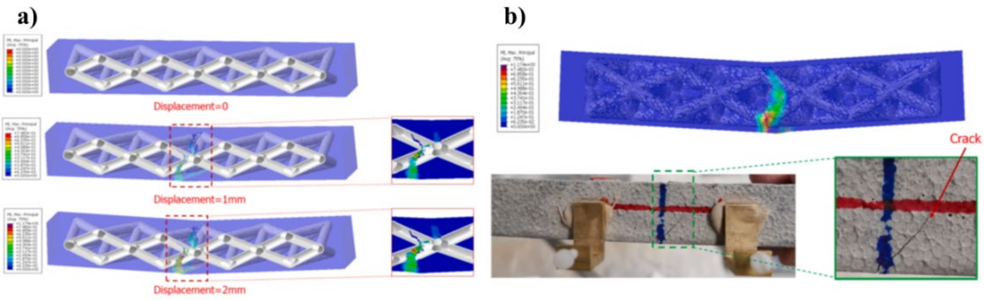

Figure 2. Analysis of the toughness of specimens exhibiting varied vascular networks. (a) Progression of internal crack formation as indicated by simulation (b) Morphological characteristics of cracks derived from both simulation and experimental observations [50]

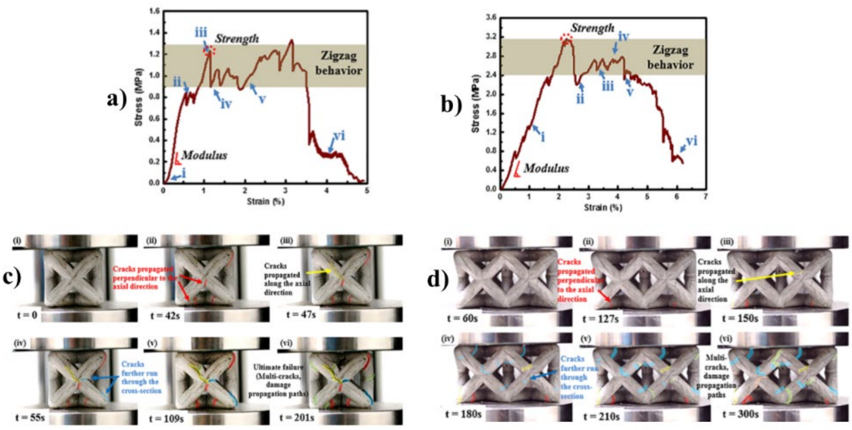

Figure 3. In situ mechanical behavior of 1 × 1 × 1 FCLM and 2 × 1 × 1 FCLMs under uniaxial compression at 20 °C. (a) Stress-strain curves for 1×1×1 FCLM are presented. (b) The deformation process is illustrated at various time intervals corresponding to (a). (c) Stress-strain curves for 2×1×1 FCLMs are shown. (d) The deformation process is depicted at various time intervals corresponding to (c). Note: Initial crack and crack propagation in FCLMs are indicated by red, yellow, and blue arrows. The deformation processes of 1×1×1 FCLM and 2×1×1 FCLM at 20 °C are available in Movies S1 and S2, SI [51]

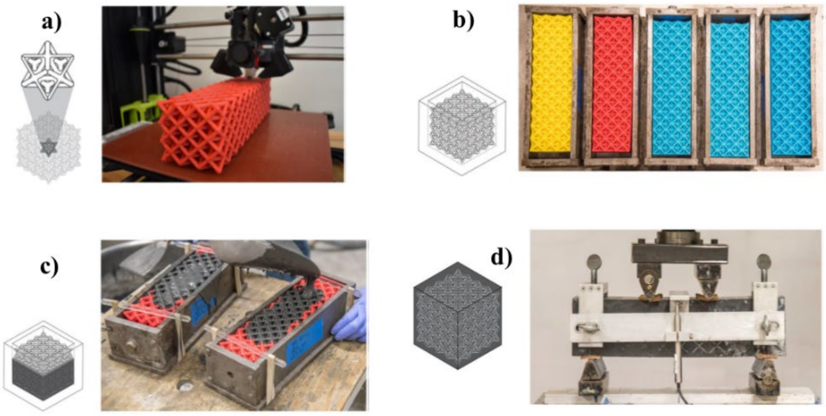

Figure 4. Fabrication of lattice-reinforced concrete beams. (a) Three-dimensional printing of the polymeric lattice structure, (b) the positioning of lattices with varying reinforcement ratios within molds, (c) the infiltration of these lattices with ultra-high-performance concrete, and (d) the resultant cured beam prepared for testing [15]

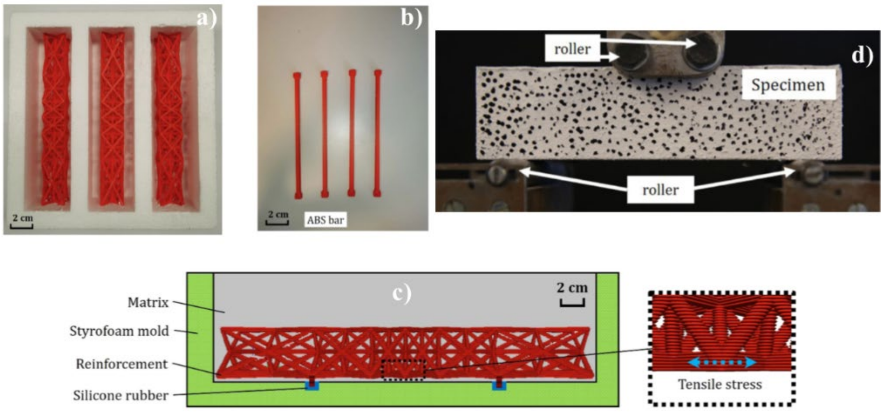

Figure 5. Schematic representations of a) the printed specimens alongside the Styrofoam mold; b) the fabricated ABS bars; c) the arrangement of the specimen within the Styrofoam mold during the casting procedure; d) the experimental configuration for four-point bending analysis [52]

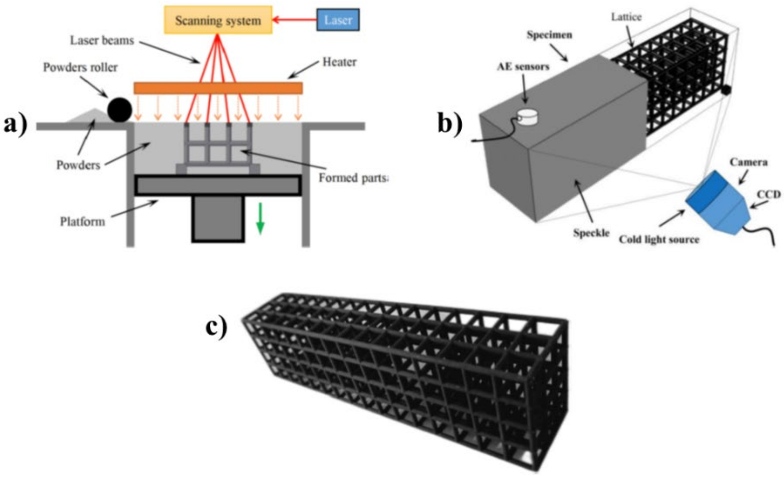

Figure 6. a) Diagram depicting SLS technology. b) Illustration of PA6 products derived from the SLS process using a cubic lattice model. c) Schematic representation of the test monitoring system [53]

Qin et al. (2022) [54] (Figure 7) examined the use of polymer lattice structures in mining backfill materials, finding significant improvements in flexibility and strength. These materials were particularly effective in addressing brittleness issues and enhancing safety in mining operations. Similarly, Dong et al. (2022) [55] (Figure 8) highlighted the environmental and mechanical advantages of alkali-activated materials reinforced with 3D-printed lattices. Efficiency Studies focusing on thermal performance have shown remarkable results. Maier et al. (2021) [56] (Figure 9) reported that paraffin-filled 3D-printed lattices significantly reduced indoor temperatures and conserved energy. Zhang et al. (2024) [57] (Figure

10) demonstrated substantial improvements in crack resistance and flexibility through optimized lattice geometries and density gradients. Alqahtani et al. (2023) [58] (Figure 11) explored the thermal efficiency of polymer lattices in cementitious composites, identifying their potential to optimize energy efficiency by fine-tuning geometric configurations. Xie et al. (2024) [59] (Figure 12) proposed a stress-absorbing approach using lattice structures to mitigate reflective cracking in layered composites, thereby extending their lifespan. Chen et al. (2023) [60] (Figure 13) and Choudhry et al. (2024) [61] (Figure 14) investigated auxetic lattice structures, showcasing their ability to improve energy absorption and ductility under both static and dynamic loads. Singh et al. (2024) [62] (Figure 15) highlighted the enhanced resilience and energy absorption capabilities of Schwarzite and zeolite-inspired geometries. Dong et al. (2024) [63] (Figure 16) emphasized the superior performance of topology-optimized lattices in improving both strength and flexibility.

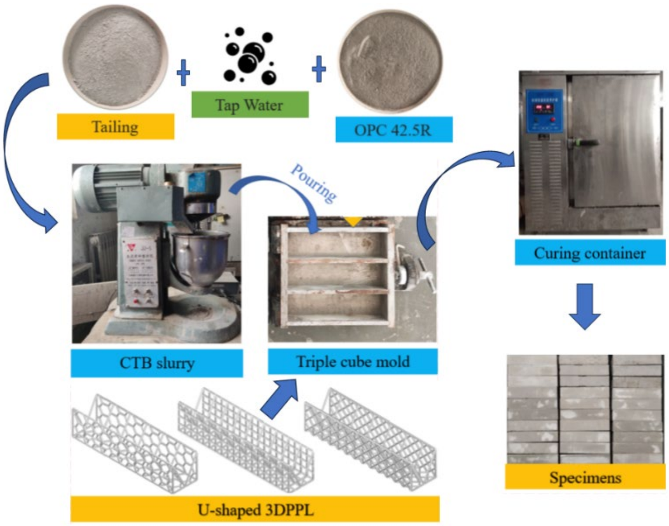

Figure 7. The methodology for the fabrication of U-shaped three-dimensional printed polymer-laden reinforced backfills [54]

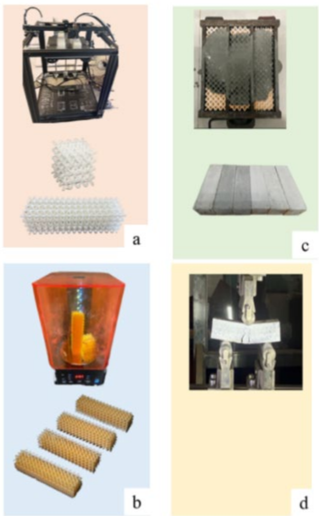

Figure 8. Fabrication and testing of the lattice-enhanced cementitious composite: (a) execution of the 3D printing methodology for lattice structures, (b) application of coating and subsequent light-curing processes, (c) infiltration of lattice structures with AAFM, and (d) assessment of flexural tension properties of the resultant composites [55]

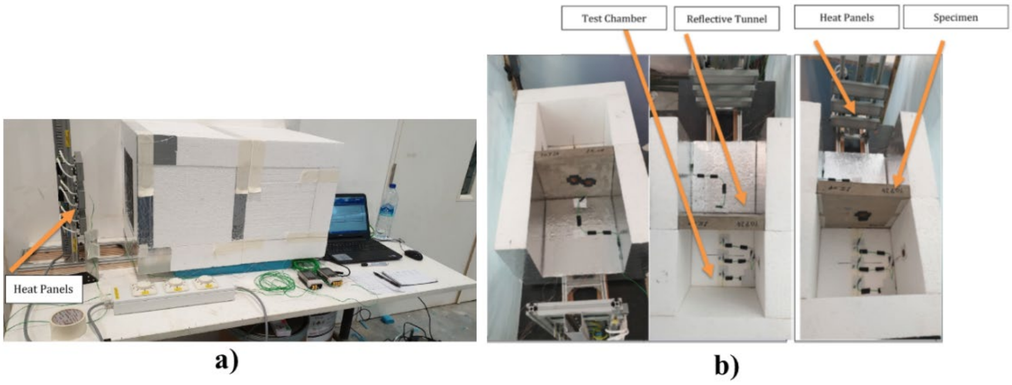

Figure 9. a) Description of the Hot Box test apparatus. b) Specifications regarding the Hot Box test apparatus [56]

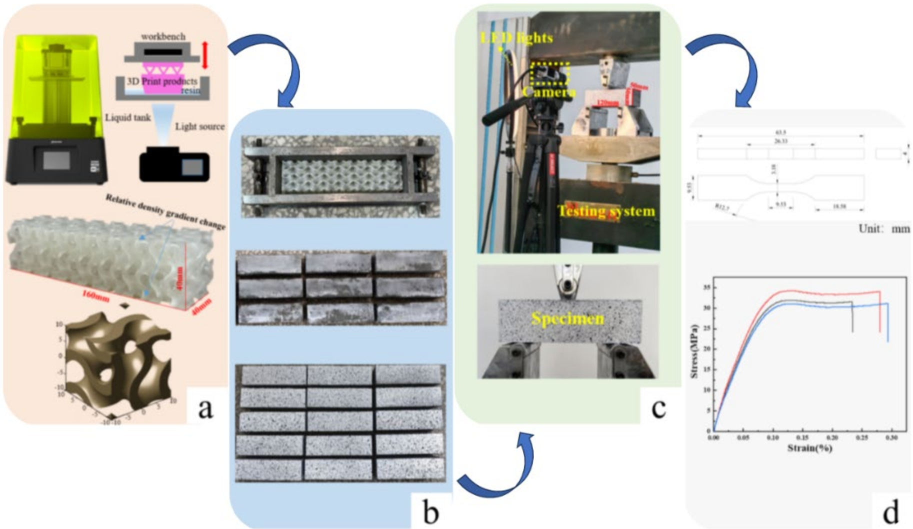

Figure 10. Fabrication and testing of the lattice-enhanced cementitious composite: (a) Implementation of 3D printing for lattice structures, (b) Preparation of specimens and DIC speckle application, (c) Configuration of test loading and DIC data acquisition system, (d) Analysis of dimensions and stress-strain characteristics of type V structures [57]

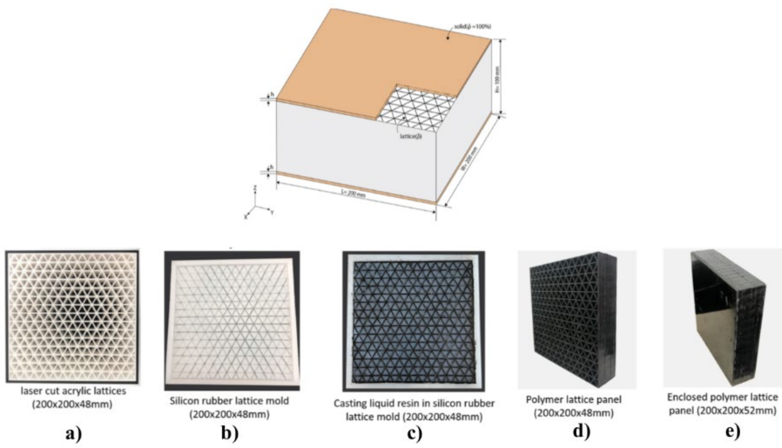

Figure 11. Schematic of a square specimen with a cross-sectional area of 0.2 m² is presented. A cutaway at the specimen's top illustrates its internal lattice topology. Acrylic triangle lattice cutting (a), silicon triangle lattice mould (b), resin casting into the mould (c), production of open-lattice panel from the mould (d), and the final enclosed lattice panel are depicted [58]

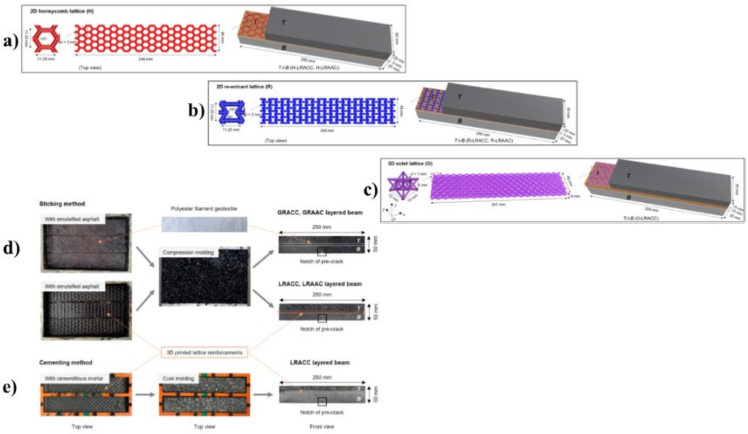

Figure 12. Lattice-reinforced composites serve as stress-absorbing interlayers in layered structures. (a) Honeycomb lattices function as interlayers; (b) Re-entrant lattices act as interlayers; (c) Octet lattices are integrated; (d) Essential procedures for interlayer adhesion methods; (e) Fundamental procedures for cementing interlayer methods [59]

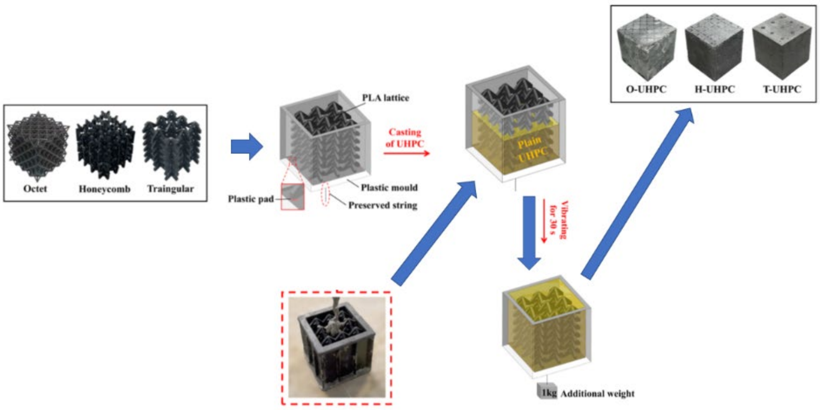

Figure 13. Schematic representation of the fabrication process for lattice-reinforced ultra-high-performance concrete specimens [60]

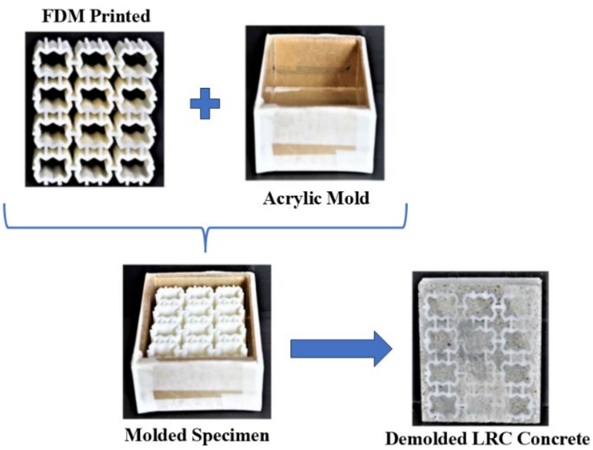

Figure 14. The process of production of lattice-reinforced concrete composites through 3D printing encompasses several critical stages [61]

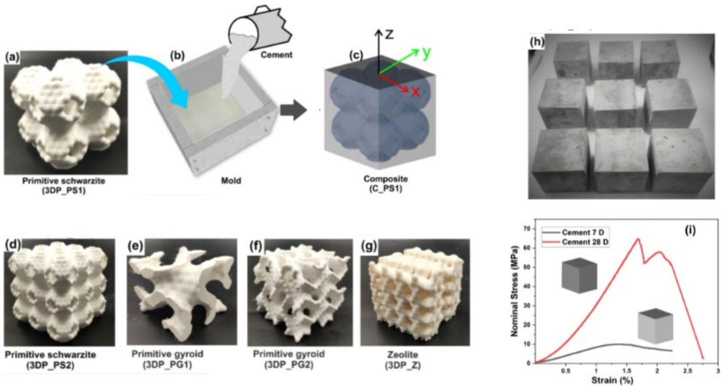

Figure 15. (a) Schematic of 3D printed polymer-cement composites. (b) Mold design for composite casting. (c) Schematic representation of the cast polymer-cement composite. (d) Illustration of Primitive Schwartzite (PS2). (e) Illustration of Primitive Gyroid (PG1). (f) Illustration of Primitive Gyroid (PG2). (g) Illustration of Zeolite (Z). (h) Optical image of composite samples post 28 days of curing. (i) Compressive stress-strain curves for cement-polymer composite cubes at 7 and 28 days [62]

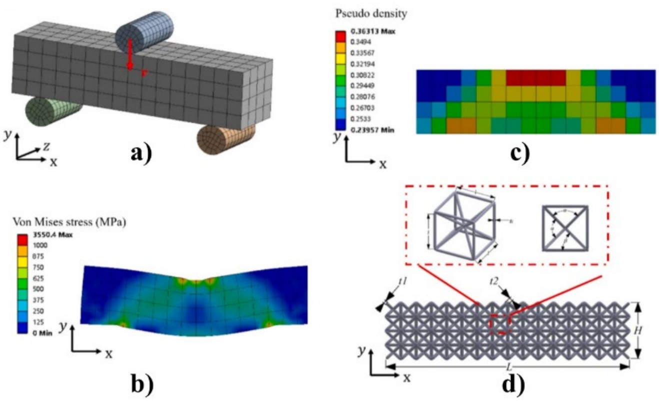

Figure 16. The methodology for generating topology-optimized lattices includes: (a) a numerical framework, (b) analysis of von Mises stress distribution, (c) pseudo distribution assessment, and (d) the introduction of the proposed lattice structure [63]

The integration of advanced lattice and polymeric reinforcements into cementitious composites has been extensively explored to improve their mechanical performance and durability. Hao et al. (2023) [29] (Figure 17) demonstrated that 3D-printed lattice structures significantly enhance compressive strength, failure modes, and durability in cementitious composites. Specifically, octagonal lattices increased compressive strength by 71.36%, altering crack patterns from single to multiple smaller cracks, thereby mitigating internal damage. This innovation provides a promising alternative to traditional steel reinforcements, particularly in corrosive environments. Xie et al. (2023) [39] (Figure 18) emphasized the optimization of lattice configurations to improve the mechanical properties of lattice-reinforced composites (LRCs). By employing a "materials by design" strategy, they achieved superior strength, ductility, and energy absorption in various lattice geometries. Notably, tesseract lattices demonstrated enhanced flexural strength, while octet lattices excelled in energy absorption. This approach underlines the potential for designing lightweight, high-performance structural systems tailored for diverse applications. Li et al. (2023) [64] (Figure 19) provided insights into the microstructural benefits of 3D-printed polymeric lattices in cementitious backfill composites (CBCs). Unlike traditional composites, 3D-printed lattices improved ductility by facilitating multi-crack formation, with the cube structure showing exceptional effectiveness. Their findings suggest a transformative shift in structural behavior, promoting tensile and shear crack resistance in CBCs. Tang et al. (2023) [32] (Figure 20) addressed the inherent brittleness of cement-based materials by introducing 3D-printed octet lattice structures. Their study highlighted substantial increases in bending capacity and toughness, achieving a 175% enhancement in peak bending load. These graded lattice structures also reduced material consumption while improving crack resistance, presenting a sustainable reinforcement strategy. Chiadighikaobi et al. (2024) [65] (Figure 21) focused on 3D-printed truss reinforcements in High-Performance Concrete (HPC). Four-point bending tests revealed that Warren trusses were most effective, enhancing flexural strength and energy absorption while reducing brittleness. This application significantly improved the ductility and weight efficiency of HPC, showcasing the versatility of 3D-printed trusses. Xu et al. (2024) [66] (Figure 22) explored surface-modified 3D-printed polymeric reinforcements, achieving doubled bonding strength with sand and steel fiber coatings compared to traditional epoxy coatings. These reinforcements improved ductility through strain-hardening and deflection-hardening behaviors. Numerical simulations corroborated the experimental findings, underscoring the pivotal role of enhanced reinforcement-mortar bonding strength in optimizing composite performance. Finally, Wu et al. (2024) [67] (Figure 23) investigated the thermal resilience of 3D-printed cementitious composites, noting that elevated temperatures adversely affected the reinforcing efficacy of lattice structures. This research underscores the need for further advancements in temperature-resistant reinforcement designs for robust construction materials.

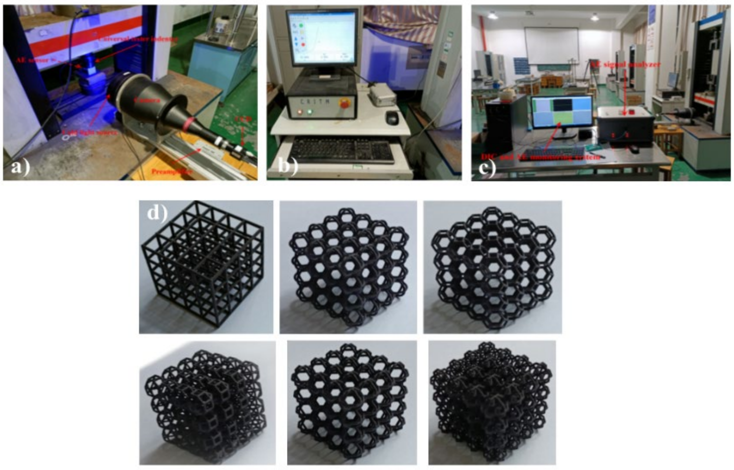

Figure 17. a) System for acquisition and loading testing of Acoustic Emission (AE) and Digital Image Correlation (DIC), b) data acquisition framework for a universal testing apparatus, c) AE and DIC data surveillance and analytical system, and d) illustration of PA6 components produced via the Multi Jet Fusion (MJF) technique (comprising 4 × 4 × 4 unit cells) [29]

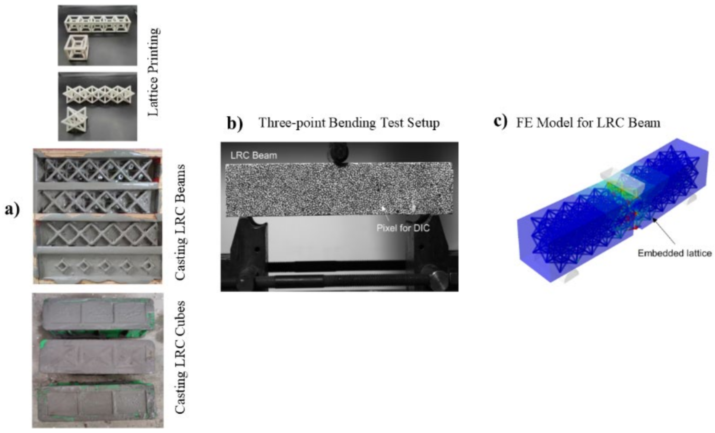

Figure 18. Fabrication and characterization of LRC structures and beams. (a) Essential procedures for LRC specimen fabrication. (b) Experimental configuration and DIC methodology for three-point bending analysis. (c) Finite element modeling of an LRC beam [39]

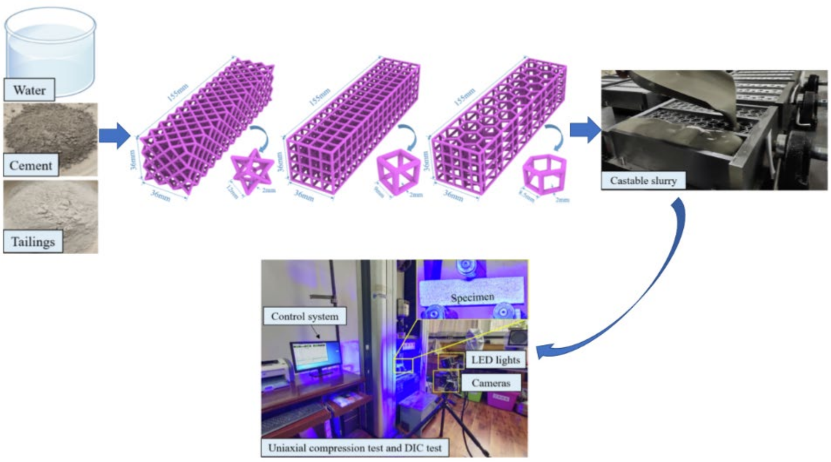

Figure 19. 3D-PPL structures include octet, cube, and hexagon models and the preparation of 3D-PPL reinforced CBC specimens involves a specific process [64]

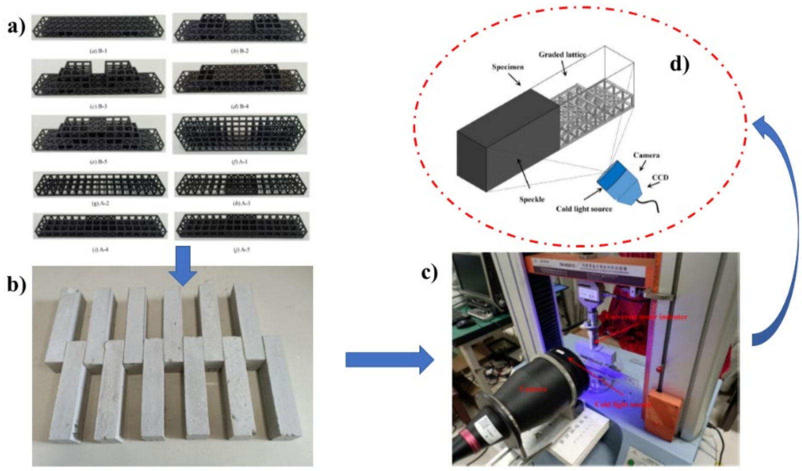

Figure 20. a) Instances of PA6 products fabricated via the MJF method, b) Cement samples prepared and aged for 28 days (partial), c) Diagrammatic representation of the test observation system, and d) The loading mechanism and DIC data collection apparatus [32]

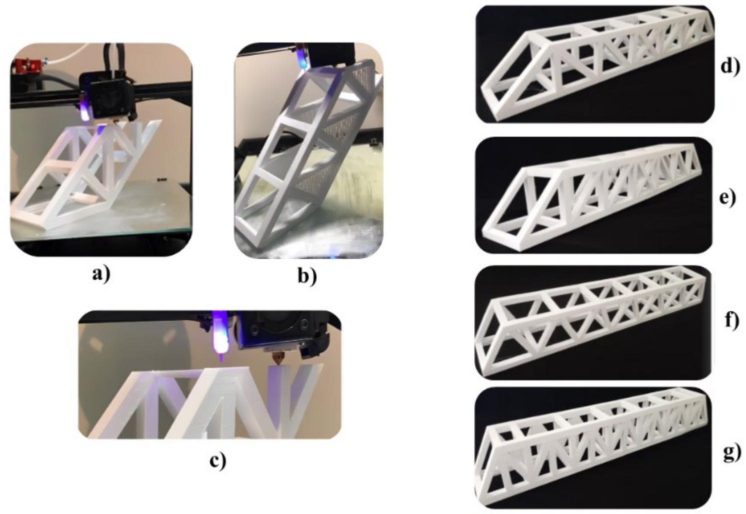

Figure 21. The FDM technique encompasses (a) a printing approach, (b) the fabrication of trusses, (c) the nozzle mechanism, and the resultant structures of (d) Pratt truss, (e) Howe truss, (f) Warren truss, and (g) Warren truss featuring vertical members [65]

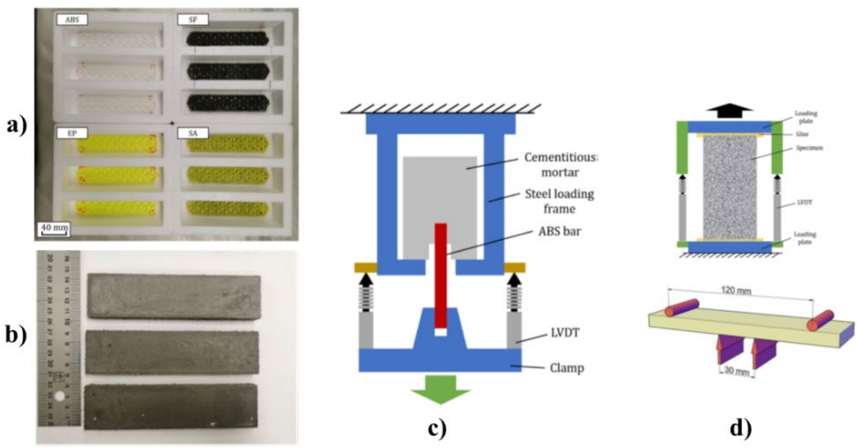

Figure 22. (a) Reinforcement embedded within Styrofoam matrices, (b) Demolded samples, (c) Diagrams of the pull-out test configuration, and (d) Diagrams of the experimental arrangement for uniaxial tensile and four-point bending assessments [66]

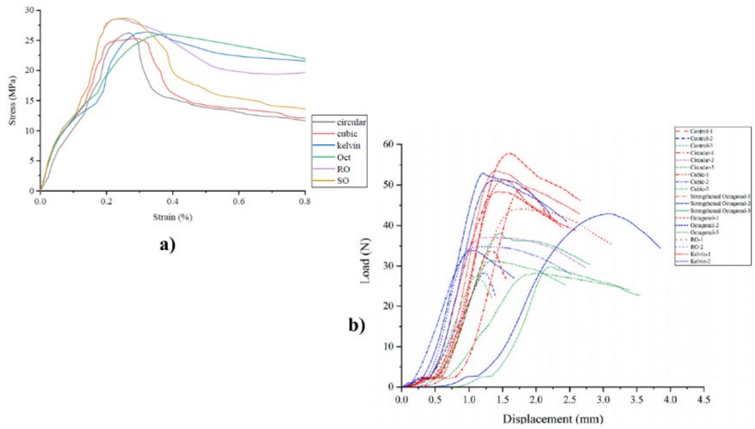

Figure 23. (a) Computational modeling of stress-strain relationships in uniaxially compressed samples with varying lattice configurations, and (b) Experimental displacement profiles from compressive testing of cementitious specimens [67]

In summary, the recent developments and studies discussed above regarding 3D-printed lattice-reinforced cement-based composites have demonstrated considerable promise for addressing the intrinsic drawbacks associated with conventional cementitious materials, including brittleness, limited tensile strength, and vulnerability to cracking. A prevalent motif within scholarly discourse is the incorporation of polymeric lattice frameworks produced via additive manufacturing techniques, which are intended to enhance mechanical characteristics, augment ductility, and confer thermal resistance. Numerous investigations have examined the effects of lattice configuration, material composition, and reinforcement volume fraction on the comprehensive performance of 3D-printed lattice-reinforced cement-based composites, yielding encouraging results that underscore the versatility and efficacy of 3D printing as a reinforcement methodology. Collectively, these findings suggest that 3D-printed lattice structures represent a revolutionary strategy to augment cement-based composites. By harnessing the precision and flexibility inherent in additive manufacturing, researchers have succeeded in designing customized lattice configurations that optimize mechanical attributes, including strength, ductility, and crack resistance, while addressing concerns related to energy efficiency and ecological sustainability. The assimilation of lattices into cementitious matrices provides substantial enhancements in both static and dynamic load-bearing capabilities, thereby facilitating the development of next-generation construction materials that are increasingly resilient, adaptable, and enduring. Future studies should concentrate on the refinement of lattice designs, exploration of novel materials for 3D printing, and assessment of long-term performance under diverse environmental conditions to fully harness the potential of this promising innovation within civil engineering and construction.

4. Advantages, Challenges, and Limitations

In modern civil engineering, the implementation of 3D-printed cement-based lattice structures offers significant benefits. Firstly, the lattice configuration provides an elevated strength-to-weight ratio, essential for developing resilient yet lightweight infrastructures, such as bridges and skyscrapers. This reduces overall mass and lowers costs related to foundational elements and structural support [3, 68, 69]. Additionally, 3D printing technology ensures precise material placement, minimizing waste and optimizing cement usage, leading to substantial financial savings and a reduced ecological footprint [53, 70]. Refining material composition and distribution enhances structural robustness and longevity, addressing the limitations of traditional construction methods.

Moreover, 3D printing enables unparalleled design versatility, facilitating the fabrication of complex geometries unattainable through conventional techniques. Engineers can customize structures to meet specific functional and aesthetic requirements, improving efficiency and fostering innovation. This adaptability supports bespoke solutions tailored to environmental contexts or architectural aspirations, encouraging novel explorations in design. Automation further accelerates construction schedules, making it advantageous for projects with stringent timelines while reducing reliance on skilled labor, thus lowering costs [71]. Automation also ensures consistency and accuracy, crucial for maintaining uniform structural integrity in large-scale projects.

Despite these benefits, challenges persist. Technical obstacles include ensuring uniform material characteristics conducive to printing and achieving precision in intricate lattice configurations to maintain structural reliability. Overcoming these issues necessitates advancements in materials science and additive manufacturing methodologies. Economic challenges include high initial capital for 3D printing technology, which may limit accessibility for smaller enterprises or projects with constrained budgets. Long-term savings in material consumption and labor efficiency, however, make this technology a persuasive investment for extensive infrastructure projects. From an environmental perspective, while 3D printing reduces waste compared to traditional methods, cement production remains energy-intensive and a significant contributor to CO_2 emissions [72]. Addressing these concerns requires sustainable alternatives to cement and enhanced recyclability to lower the carbon footprint. In addition, 3D-printed cement-based lattice structures demonstrate material efficiency and sustainability but have strengths and limitations compared to traditional reinforced concrete systems. Lattice structures exhibit a superior strength-to-weight ratio and crack resistance owing to their optimized stress distribution. However, traditional reinforced concrete outperforms compressive strength and load-bearing capacity, making it preferable for high-load scenarios. Economically, 3D printing reduces material waste and labor costs, although it incurs high initial investments in specialized equipment and materials. Conversely, conventional concrete benefits from established supply chains and cost-effective, large-scale production. In terms of sustainability, 3D-printed lattice structures use less cement and produce lower carbon emissions, aligning with the environmental objectives. Nonetheless, challenges, such as energy-intensive printing processes and the need for advanced material formulations, must be resolved for large-scale adoption. This comparison underscores the innovative aspects of 3D-printed lattice structures while recognizing the challenges to their widespread implementation.

Beyond conventional uses, 3D-printed cement-based lattice structures open new possibilities in architectural and engineering design [59, 73]. They enhance disaster resilience by enabling structures that withstand seismic forces through energy-dissipating lattice configurations. Moreover, intelligent components such as embedded sensors for structural monitoring and integrated thermal insulation augment functionality, safety, and operational efficiency. Architecturally, this technology allows for unprecedented creativity, supporting innovative designs that align with sustainable principles by improving material efficiency and conserving energy. Future developments in materials science are expected to produce novel cement composites with improved mechanical properties, durability, and sustainability, facilitating the construction of robust and environmentally conscious buildings. Advances in printing technologies will also enhance precision, reliability, and scalability, making 3D printing more accessible and economically viable across a diverse range of applications. Furthermore, the integration of robotics and AI-based design optimization [74] promises to refine construction methodologies, reducing project durations, lowering costs, and enhancing efficiency. These innovations represent a significant opportunity to revolutionize the construction industry by leveraging automation and data-driven decision-making for improved quality, safety, and sustainability [75].

In summary, 3D-printed cement-based lattice structures are transforming civil engineering by improving structural integrity, enhancing sustainability, and increasing design flexibility. Despite challenges [34, 51, 67], ongoing research and practical implementations are expanding their potential applications. Continued scholarly investigation and empirical analysis are essential to addressing these challenges and realizing the full potential of this innovative technology. The adoption of these advancements signifies not only progress in engineering practices but also a commitment to fostering a more resilient, efficient, and sustainable built environment for future generations.

3D-printed cement-based lattice structures offer potential in civil engineering yet face significant implementation challenges. Scalability is a primary concern, necessitating advancements in printing technologies for large-scale infrastructure projects. Cost factors also affect technology adoption. Despite reducing material waste and improving performance, the high initial investment in specialized equipment limits accessibility. Regulatory hurdles remain, as building codes for 3D-printed structures are still evolving. Collaboration among industry stakeholders, regulators, and researchers is vital for developing guidelines that promote the integration of 3D-printed solutions in construction. Overcoming these challenges is essential for harnessing the full capabilities of 3D printing in reconstruction, bridge-building, and tunnel engineering.

5. Applications in Civil Engineering

3D-printed polymer lattice-reinforced structures, predominantly composed of cement-based materials, hold significant potential in contemporary civil engineering applications. These structures enhance both performance and sustainability in diverse environmental contexts [71, 76]. The integration of cement and polymeric materials in lattice formations enables the creation of lightweight components with remarkable strength while allowing extensive customization to meet the varied requirements of civil engineering scenarios [72]. One key application of these advanced technologies is in load-bearing elements critical to the stability of buildings and bridges [77]. The geometric flexibility of lattice designs significantly reduces material usage while maintaining structural integrity [65]. By incorporating polymer reinforcements, these structures achieve enhanced durability, corrosion resistance, and mechanical performance, making them ideal for high-stress environments such as bridge spans, abutments, and support systems. The reduced material weight further contributes to cost efficiency and enables the construction of complex and aesthetically appealing architectural forms that enhance the visual and functional quality of built environments [56].

In high-rise buildings and extensive infrastructure systems, these structures expedite the assembly of facades, internal partitions, and load-bearing systems essential to building integrity [30, 71]. Their ability to accommodate intricate geometric forms allows architects and engineers to transcend the limitations of traditional construction methods, advancing sustainable and energy-efficient designs. Polymers within these structures improve thermal insulation and moisture resistance, making them particularly suitable for environmentally sustainable projects [78]. Additionally, these structures demonstrate promise in tunnel construction, retaining walls, and coastal defense mechanisms. Their lightweight yet resilient characteristics, combined with the adaptability of additive manufacturing, enable them to conform to site-specific conditions and complex geometries that would be challenging or costly with conventional methods. This versatility makes them particularly effective in regions prone to seismic activity or erosion, where traditional materials often underperform [65, 79].

6. Key Drawbacks and Challenges in 3D Printed Cementitious Composites

The innovative technology of 3D-printed lattice-reinforced cementitious composites is gaining traction within civil engineering due to its advantages, including improved mechanical properties and unprecedented design flexibility [63, 69]. However, several challenges must be addressed to optimize its practical applications [80]. One critical concern is the compatibility and bonding efficacy between the composite components. Weak bonding at the interface can lead to structural vulnerabilities, compromising the composite's integrity [52, 65, 81]. Additionally, differences in thermal and mechanical properties between the lattice and cementitious matrix can result in stresses that may cause delamination and impact performance [82]. Addressing these issues is essential for successful implementation in real-world scenarios [83]. On the other hand, printing precision and quality control present further challenges in the fabrication of lattice structures [84, 85]. Any inaccuracies during the printing process can result in defects, affecting the mechanical properties of the composite material [86, 87]. Ensuring consistent quality throughout the printing process is crucial, especially in large-scale applications requiring high precision and reliability [88, 89]. Additionally, the high costs associated with 3D printing equipment and materials remain significant barriers to widespread adoption [70]. While 3D printing offers long-term savings through material efficiency [90], the initial investment for infrastructure remains substantial [91]. Strategic approaches are needed to balance these financial challenges with the potential benefits of the technology.

The complexity of designing and analyzing lattice structures further adds to the challenges. Advanced computational tools and specialized expertise are required for effective modeling and simulation, which may limit accessibility for some engineering firms. Durability and long-term performance remain critical areas of research, as exposure to environmental conditions, cyclic loading, and chemical attacks can significantly affect structural integrity [92, 93]. Addressing these durability concerns is vital for ensuring the reliability of lattice-reinforced composites over time [94]. On the other hand, a lack of standardization and regulatory acceptance also hinders the integration of these materials into the construction industry [95]. The absence of universally recognized testing methods complicates the validation and approval processes, leading to delays in adoption [96]. Collaboration among design, manufacturing, and construction teams is critical but often challenging, requiring reassessment of workflows to improve efficiency [97]. Encouraging innovation within regulatory frameworks may facilitate faster acceptance of these advanced composites in mainstream construction.

In summary, while 3D-printed lattice-reinforced cementitious composites hold immense potential, overcoming challenges related to material compatibility, precision, costs, standardization, and durability is essential for their successful implementation. Addressing these multifaceted issues through collaborative efforts and continued research will unlock the full potential of this technology to shape the future of construction [68, 98].

7. Future Directions and Research Needs

When exploring the future trajectories and research priorities for the development and implementation of 3D-printed cement-based lattice structures, it is evident that advancements in 3D-printing technology are transforming contemporary construction methodologies [68, 70]. Innovations such as high-speed printing techniques significantly enhance operational efficiency and scalability, essential for large-scale construction projects [77]. Similarly, multi-material printing technologies [73, 99] improve the structural integrity and functionality of printed components, accommodating diverse design requirements. Enhanced printing resolution allows for the creation of intricate lattice configurations with precision, while real-time monitoring and adaptive control mechanisms ensure quality and consistency throughout the printing process [34, 100]. The integration of robotics further automates construction tasks [70, 101], reducing labor costs [20] and improving assembly accuracy. Hybrid printing methods, which combine 3D-printing with conventional construction practices, optimize material usage and structural integrity.

Research priorities include developing advanced cementitious formulations and additives to improve printability, strength, and durability, alongside investigating the mechanical behavior of these structures under various loading conditions. Long-term durability assessments are critical to understanding resistance to environmental challenges and aging processes. Scaling production while maintaining structural integrity and cost-effectiveness is another essential area of focus.

Comprehensive life cycle assessments [102] are crucial for evaluating environmental impacts and identifying opportunities for sustainability improvements. Optimized design methodologies and advanced additive manufacturing techniques prioritize material efficiency, energy conservation, and the development of recyclable materials to minimize environmental impact. Efforts to reduce carbon footprints through sustainable manufacturing processes, improved transportation logistics, and circular economy principles further enhance these initiatives [57, 73, 103]. The use of locally sourced materials and decentralized production methods mitigates transportation-related impacts, positioning 3D-printed cement-based lattice structures as pivotal in developing sustainable and resilient infrastructure systems [100].

8. Conclusion

This study significantly advances the understanding of 3D-printed cement-based lattice structures by integrating their mechanical, material, and environmental benefits. This investigation uniquely focuses on lattice structures to improve the mechanical properties and sustainability, in contrast to traditional reviews of 3D printing in construction. By unifying scattered research and analyzing various lattice geometries, this study offers a novel framework for improving the structural efficiency and addressing scalability in sustainable construction. These findings enhance academic dialogue and provide actionable insights for engineers and policymakers regarding the implementation of additive manufacturing in extensive infrastructure initiatives. In conclusion, the advent of 3D-printed lattice structures composed of cement-based materials marks a revolutionary advancement in civil engineering, offering substantial improvements in structural design, material utilization, and sustainability. Conventional cementitious materials have long been challenged by inherent weaknesses, such as low tensile strength and susceptibility to cracking, which are traditionally addressed through steel reinforcements. However, these solutions introduce complications like corrosion. In contrast, 3D printing enables the meticulous customization of lattice structures, optimizing material usage while enhancing structural integrity. This capability reduces material consumption and fosters sustainable construction practices by minimizing the environmental impact of traditional methods. Beyond efficiency, this technology enables the creation of resilient structures capable of enduring environmental stressors and the test of time. The integration of 3D-printed cement-based lattice structures heralds a new era in civil engineering, prioritizing both sustainability and superior structural performance.

The incorporation of lattice reinforcement amplifies these advantages by optimizing load distribution among interconnected struts and nodes, enhancing structural resilience and resistance to deformation under various stress conditions. This approach mitigates risks associated with localized stress concentrations that can lead to premature failure. Furthermore, these structures demonstrate exceptional durability and resilience to environmental challenges such as cyclic loading and temperature fluctuations. The interconnected voids in lattice structures facilitate efficient stress distribution, reducing crack propagation and bolstering long-term stability. This durability is especially crucial for infrastructure applications, where longevity and maintenance costs are significant considerations. The integration of lattice reinforcement not only enhances structural integrity but also promotes sustainability and economic viability, offering innovative solutions for modern construction challenges.

Looking ahead, ongoing advancements in material science and additive manufacturing techniques are poised to refine the mechanical properties, scalability, and sustainability of these structures. Emerging printing technologies, multi-material capabilities, and robotic automation hold immense potential for streamlining construction processes and expanding the applications of 3D-printed cement-based lattice structures. These advancements are anticipated to revolutionize sectors such as building construction, bridge development, disaster resilience, and even space exploration. By addressing the limitations of traditional materials while championing resource efficiency, these structures represent a paradigm shift in construction methodologies. Their role in developing resilient and sustainable infrastructure will be vital for the future.

The continued commitment to interdisciplinary collaboration and innovation is essential to unlocking the full potential of these advanced structures. Such efforts will shape a built environment capable of addressing the multifaceted challenges of the 21st century. Stakeholders across disciplines must explore the capabilities of these technologies to revolutionize global construction practices. Ultimately, integrating these advancements into mainstream construction has the potential to redefine infrastructure development, ensuring we are better prepared to meet the evolving demands of the modern world.

This review addresses a significant gap in the literature by integrating both theoretical and practical benefits of cement-based 3D-printed lattice structures. While much current research focuses on singular geometries or empirical results, this study evaluates the fundamental principles of lattice design and their implications for sustainability and structural efficacy. These insights provide a robust foundation for future experimental and theoretical inquiries in civil engineering.

9. Generative AI statement

The author declares that Generative AI, specifically ChatGPT with basic version, was utilized for language editing during the preparation of this manuscript.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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