Comparative Analysis of Aerogels, Metamaterials, and 3D-Printed Concrete for Sustainable and High-Performance Construction

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Abstract

This paper presents a comparative analysis of three innovative construction materials, such as aerogels, metamaterials, and 3D-printed concrete, to evaluate their potential in advancing sustainable and high-performance building design. A qualitative literature review synthesizes findings from recent experiments and case studies to assess each material's structural performance, thermal efficiency, environmental impact, and practical feasibility. Results show that aerogels offer exceptional insulation but remain limited by high production costs and fragility; metamaterials demonstrate strong potential for seismic and vibration control, though large-scale implementation is still experimental; and 3D-printed concrete provides high mechanical strength, design flexibility, and reduced material waste. Overall, the study underscores that context-specific material selection, balancing performance, cost, and scalability, is essential for future sustainable construction and calls for further research to optimize fabrication methods and hybrid material systems.

1 Introduction

Construction materials are the foundation of the built environment and have influenced human development from ancient civilizations to modern cities. The materials used in buildings, roads, and infrastructure have shaped how societies grow and adapt over time. Today, the construction industry is undergoing major change as it seeks greater sustainability, efficiency, and resilience to address global challenges such as climate change and rapid urbanization. Traditional materials, including concrete, steel, and timber, often struggle to meet these goals because of their environmental impact, high energy demand, and limited flexibility [1].

In response to these challenges, several new materials have emerged with the potential to revolutionize construction practices.

Aerogel is a synthetic porous ultralight material derived from a gel, in which the liquid component has been replaced with a gas [2]. The most common form, silica aerogel, is composed primarily of silicon dioxide and produced through a sol-gel preparation process. Aerogels, known for their ultra-lightweight structure and exceptional thermal insulation properties, consist of up to 99.8% air, which makes them the lowest-density solids and highly effective insulators. Their nanoporous structure minimizes heat transfer through convection, conduction, and radiation, making them particularly useful for energy-efficient buildings [3]. An example of aerogel as a construction material is shown in Fig. 1.

Metamaterials are artificially engineered materials with periodic structures not found in nature, allowing unprecedented control over physical properties such as acoustic, electromagnetic, and seismic wave behavior. In civil engineering, they have been proposed for seismic shielding applications, where specially designed foundations can reflect or absorb earthquake waves [4]. An example is shown in Fig.1.

3D-printed concrete (3DPC) represents a transformative shift in construction methodology by using automated, layer-by-layer deposition through robotic systems (Fig. 2A), [5]. Compared to traditional concrete, 3DPC allows for highly customized geometries, precise material placement, and reduced formwork, material waste, and labor costs. Its digital-driven flexibility supports rapid prototyping, on-site manufacturing, and architectural innovation. Moreover, 3DPC has significant potential for low-cost housing and post-disaster reconstruction by enabling fast, scalable, and automated building without traditional scaffolding [6][5].

Despite the growing amount of literature exploring each material individually, there is a lack of comparative analysis that evaluates their relative advantages and limitations across unified performance metrics. Most studies focus narrowly on either thermal performance, structural behavior, or environmental impact, leaving a gap in holistic assessments.

This study aims to address that gap. Through a critical literature review and comparative framework, this paper analyzes the performance and potential of aerogels, metamaterials, and 3D-printed concrete. By evaluating these materials against key criteria such as structural performance, sustainability, economic value, and future potential, this research contributes to ongoing efforts to identify innovative solutions for sustainable and resilient construction.

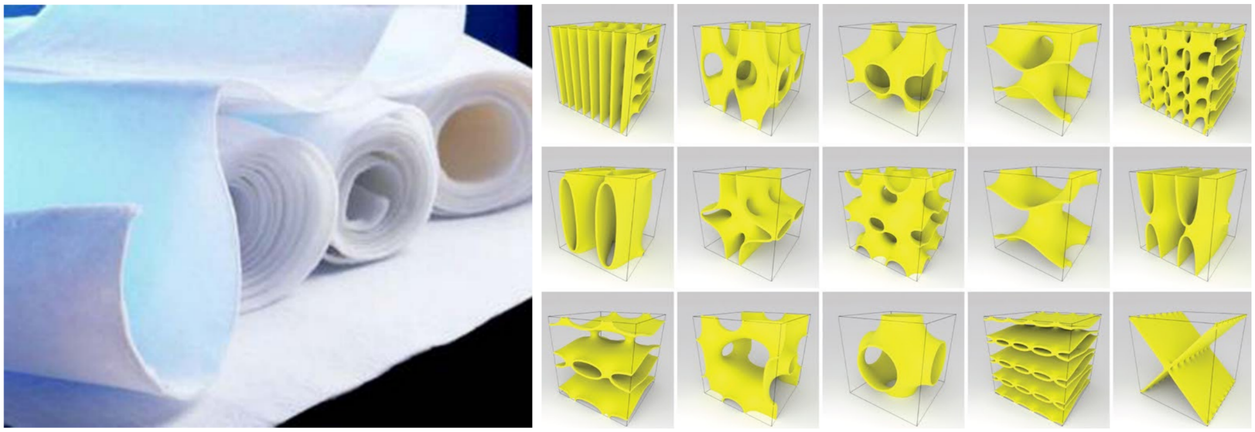

Figure 1: Examples of Aerogel [3] and Metamaterials as construction materials [7].

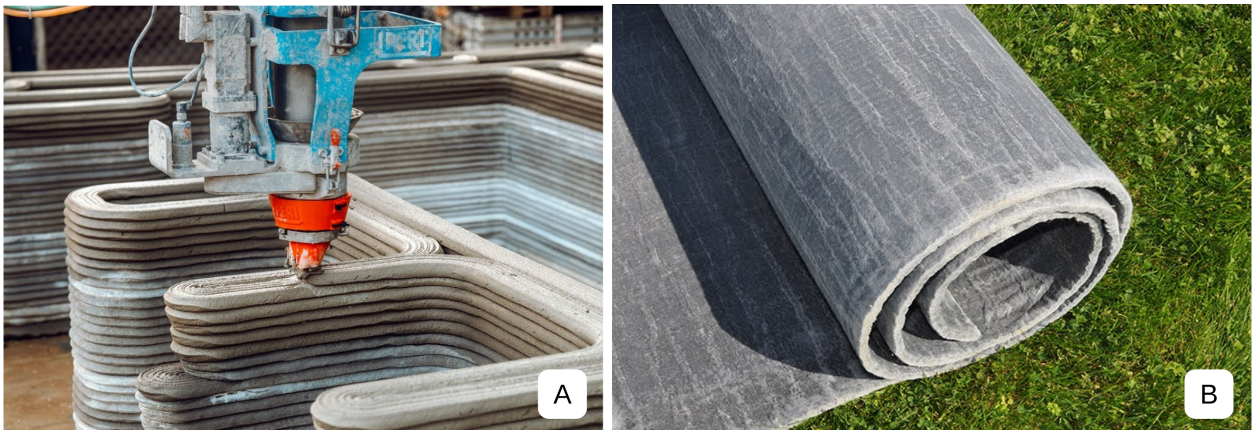

Figure 2: A) 3-DPC use in Construction (Parametric Architecture, 2024 [8]). B) 10 mm Spaceloft ready to use (Aspen Aerogel, n.d. [9]).

2 Methodology

A qualitative literature review was conducted to compare new construction materials such as aerogels, metamaterials, and 3D-printed concrete. The review focused on peer-reviewed articles, recent publications, and case studies discussing the applications, advantages, limitations, and real-world performance of these materials. Each source was analyzed to identify common themes and compare material performance across structural, thermal, environmental, and economic dimensions. Tables and charts were used to present findings clearly and concisely. This approach helped highlight trends, research gaps, and insights that inform future directions for sustainable and high-performance construction materials.

3 Literature Review

3.1. Aerogels in Construction

Aerogels were first invented in 1931 and have gained significant attention in the building materials industry due to their exceptional thermal insulation properties, ultra-low densities, and high porosity. Silica aerogels, in particular, are widely recognized for their nanoporous structure and extremely low thermal conductivities, typically between 0.013 to 0.020 W/(m·K), making them some of the most effective insulating materials available today [10]. Their potential for reducing energy consumption in buildings has prompted numerous studies into their application, development, and limitations within the context of sustainable construction. In building insulation, aerogels are utilized primarily in three forms: opaque, translucent, and transparent applications, each optimized for different building functions.

Opaque aerogel blankets, such as Spaceloft by Aspen Aerogels, provide excellent thermal insulation with a conductivity of around 0.013 W/(m·K) at 273 K (Fig. 2B). These sheets, as thin as 10 mm, are especially useful for retrofitting older masonry buildings where thicker traditional insulation is not feasible. Research shows they outperform materials like mineral wool and polystyrene by 2-2.5 times, significantly reducing heat loss in timber and steel structures [3].

Translucent aerogels are used in daylighting systems, balancing insulation with natural light transmission. These systems typically use granular silica aerogel sandwiched between PMMA or glass panes, sometimes with argon or krypton gas fill. They achieve U-values between 0.37 and 0.56 W/(m^2·K) while allowing visible light transmission of 0.19 to 0.54. Two examples of translucent aerogel insulation applied over large areas in new buildings for daylighting purposes are shown in Fig. 3.

Figure 3: Two examples of translucent aerogel insulation as a thermal insulation solution for daylighting [3].

Transparent aerogels are being explored for windows, particularly in north-facing applications where direct sunlight scattering is a concern. With a 20 mm aerogel layer, these glazing systems can reach U-values as low as 0.5 W/(m^2·K) while maintaining over 75% solar transmittance [10]. Though still limited by cost and clarity issues, their performance suggests promising future applications.

In addition to insulation, aerogels can also capture carbon dioxide, combining passive thermal performance with active carbon sequestration. Chemically modified aerogels can adsorb up to 7 mmol/g of CO_2 while retaining low thermal conductivity, though this often reduces mechanical strength, making careful curing essential [11].

Cellulose-based aerogels provide a biodegradable alternative to silica types, offering thermal conductivities below 0.025 W/(m·K). However, challenges like flammability, moisture sensitivity, and limited scalability remain, with surface treatments and chemical crosslinking used to enhance durability [12].

Aerogels can also be incorporated into concrete, forming composites with thermal conductivities between 0.16–0.37 W/(m·K) and compressive strengths of 3–24 MPa. These materials show potential for structural use, although long-term durability in varying environmental conditions is still a concern [13].

A study by Kotov et al. [14] evaluated the role of aerogels in improving the thermal performance of buildings created using additive manufacturing. The structure is shown in Fig.4. The study finds that aerogel blankets, with thermal conductivities around 0.0227 W/(m·K), significantly reduce heat transmission in building envelopes, with U-values improving from 1.18 to 0.53 W/(m^2·K). When added to concrete, aerogel powder decreases thermal conductivity by 25%, enhancing the insulation properties of the material. Computational simulations also demonstrate that partial aerogel filling in cavity walls prevents condensation and optimizes material use for thermal efficiency. Overall, the use of aerogels in additive construction demonstrates significant potential for enhancing energy efficiency, though cost and material optimization remain key challenges for widespread adoption [14].

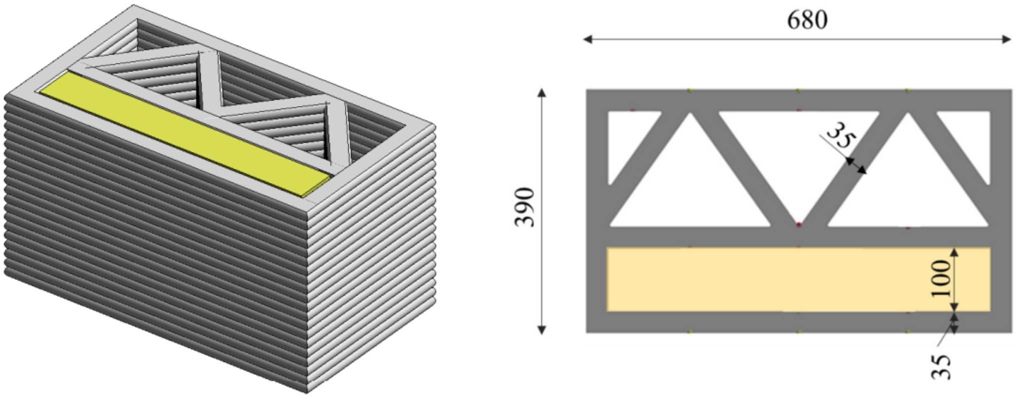

Figure 4: Aerogel Insulated Additive Manufacturing Structure [14].

Although aerogels have excellent thermal performance, several challenges still limit their use in construction. One major issue is their high cost, which is about five to ten times higher than traditional insulation materials. This is mainly due to the energy-intensive drying process used during production [2]. In addition, aerogels are difficult to recycle at the end of their life, which creates concerns about long-term sustainability, even though they reduce energy use in buildings. New production methods, such as ambient pressure drying and the use of industrial waste as a source of silica, are being explored to reduce both the cost and environmental impact of aerogels [11].

3.2. Metamaterials in Construction

Metamaterials are a novel class of engineered materials that exhibit extraordinary properties not found in nature due to their unique internal structures rather than their chemical composition. These materials can be precisely designed to control the propagation of mechanical waves, such as seismic vibrations and shockwaves, by leveraging structural periodicity or local resonance effects [15]. The manipulation of wave behavior enables metamaterials to serve as protective elements in infrastructure, especially in seismic and blast-resistant applications, offering performance characteristics far beyond traditional materials.

In seismic engineering, metamaterials have shown potential in creating seismic shields by producing frequency band gaps, which are ranges in which mechanical wave propagation is suppressed. These gaps result from the periodic structuring of subcomponents within the metamaterial foundation, enabling the deflection or reflection of harmful seismic waves [16]. Additionally, local resonance metamaterials employ embedded resonant units that target and dissipate vibrational energy at specific frequencies. Experimental setups using underground pillars with steel cores and rubber coatings achieved up to an 80% reduction in energy transmission at 9 Hz, highlighting their capacity to mitigate frequencies associated with structural failure [17].

For blast mitigation, metamaterials have been developed to control the propagation of shockwaves through tailored geometry and material combinations. Auxetic structures, materials exhibiting a negative Poisson's ratio, have emerged as particularly effective due to their ability to expand laterally under tension, thereby enhancing energy dissipation. When subjected to blast loading equivalent to 1 kg of TNT, 3D-printed auxetic honeycomb panels absorbed 35% more energy than conventional materials and limited deformation on the protected side to under 10 mm, indicating high performance under localized impact [18]. Another study employed auxetic re-entrant honeycomb metamaterial cores with tunable (graded) stiffness within sandwich panels. Field blast tests and validated simulations demonstrate that the variable-stiffness auxetic core reduces back-face maximum displacement to 11.9 mm (compared to 63.0 mm for a non-tuned auxetic core) and increases total absorbed energy to 4.61 kJ (approximately 27.5% higher than the baseline). The auxetic core itself contributes about 75–82% of the total energy dissipation under blast loading, confirming that stiffness-graded auxetic stacks effectively diffuse shock energy [19].

Several field-scale experiments have also been conducted to validate the theoretical advantages of seismic metamaterials. The study by Brule et al. [4] implemented a grid of vertical boreholes that are 0.32 m in diameter, 5 m deep, spaced 1.73 m apart in silty clay soil, designed to redirect surface seismic waves generated by a 50 Hz source. Results showed significant wave reflection beyond the borehole array and a 2.3-fold increase in elastic energy concentration near the wave source, confirming the metamaterial's ability to manipulate wave fields for protective applications [4]. A photograph of the experimental site is shown in Fig. 5.

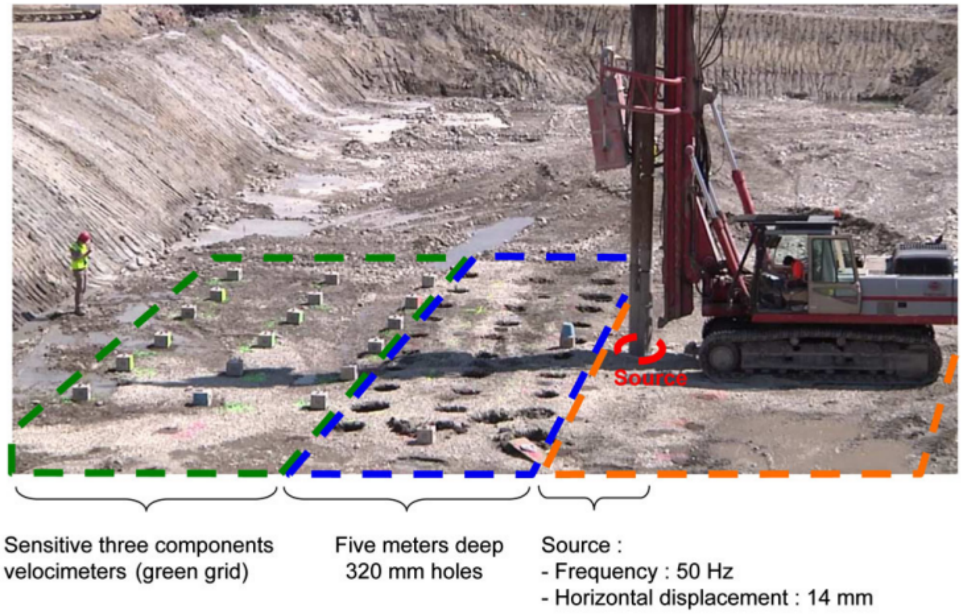

Figure 5: Photograph of the site of the seismic metamaterial experiment [4].

Another investigation by Zhang et al. [20] explored a periodic array of square holes to study the attenuation of Rayleigh and Love waves. Numerical simulations and field measurements revealed broad attenuation band gaps between 40–60 Hz for Rayleigh waves and 43–56 Hz for Love waves. An inversion phenomenon was observed in the attenuation pattern around 50 Hz, where Love waves became more attenuated below the threshold while Rayleigh waves dominated above it, highlighting the complex interplay between wave types and metamaterial geometry [20]. A photograph of the experimental site is shown in Fig. 6.

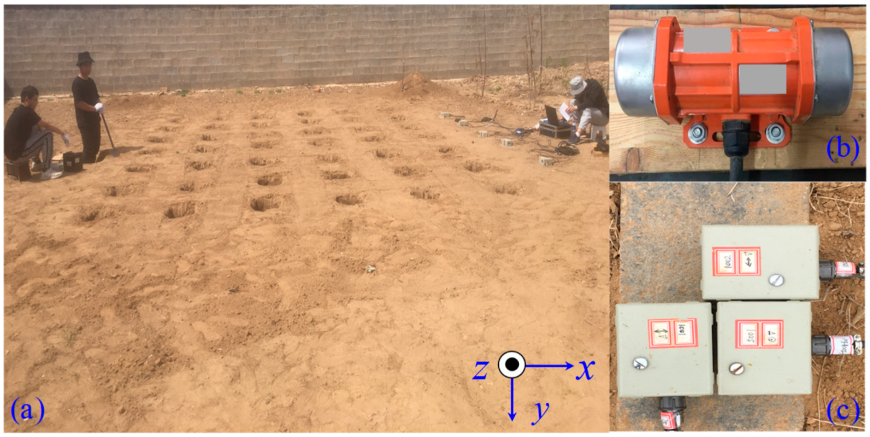

Figure 6: Photos of experimental site (a), eccentric vibrator (b), and sensors (c) [20].

3.3. 3D-Printed Concrete in Construction

3D-printed concrete (3DPC) is an innovative construction technology that enables the fabrication of building components layer by layer, using specialized concrete mixtures and printers. This method allows for the creation of complex geometries without the need for traditional formwork, offering significant advantages in design flexibility and material efficiency [21]. This technology has been applied in residential, commercial, and infrastructure projects.

In residential construction, 3DPC has been employed to build homes rapidly and cost-effectively. For instance, the Milestone Project in Eindhoven, Netherlands [22], is the world's first legally habitable 3D printed concrete house, completed in 2021 as part of a five-house series. The first house features structurally load-bearing, curved concrete walls printed off-site and assembled on prefabricated slabs, combining two wall types with and without infill patterns for insulation and stability. The house was certified for a 50-year service life and met durability and energy efficiency standards [22]. The finished house is shown in Fig. 7.

Figure 7: The first 3D printed house of Project Milestone [22].

The commercial sector has also embraced 3DPC. Starbucks opened its first 3D-printed store in Brownsville, Texas, featuring unique concrete tube walls produced by robotic arms, showcasing the aesthetic possibilities of this technology [23]. Additionally, ICON's development of a 3D-printed desert oasis in Marfa, Texas, which includes hotel units and private homes, illustrates the scalability of 3DPC in hospitality projects [24]. Both are shown in Fig. 8.

Figure 8: First 3D-printed store [23] and 3D-printed desert oasis in Texas [24].

In terms of infrastructure, 3DPC has been utilized to construct bridges and other public works. A key infrastructure application of 3D-printed concrete is the world's longest 3D-printed concrete pedestrian bridge, which is a 29-meter-long pedestrian and cyclist bridge in Nijmegen, Netherlands . Developed by Eindhoven University of Technology and Rijkswaterstaat, the bridge comprises five prestressed girders made of 3D-printed segments, joined with epoxy and enclosed by reinforced concrete anchor blocks. Each girder includes bottle-shaped hollow sections to reduce material use. Full-scale bending tests showed the girders could withstand loads over 3× the ultimate design load without failure. Final structural tests confirmed elastic behavior under 100% service loads, validating the bridge's safety for public use [25]. Final bridge assembly is shown in Fig. 9.

Figure 9: Assembly of the final bridge on location [25].

Another area of focus for 3DCP is the integration of passive energy systems into printed structures. Recent advancements in the design of 3D-printed concrete walls have led to the development of systems that can support passive energy functions, such as thermal insulation and energy generation. For instance, 3D-printed concrete building envelopes have been integrated with living wall systems, demonstrating how printed geometries can be optimized to improve energy efficiency by reducing a building's annual energy consumption [26]. This innovation highlights the potential of 3DCP in the development of sustainable architecture that contributes to energy savings and environmental conservation.

4 Analysis

This section presents a detailed comparative analysis of three construction materials, such as aerogels, 3D-printed concrete, and metamaterials, across multiple performance characteristics. The goal is to evaluate their feasibility for sustainable construction applications based on structural, thermal, environmental, and economic criteria.

4.1. Structural Performance

The structural performance of materials is key to their use in supporting loads and construction. This performance is most commonly evaluated using parameters such as compressive strength, flexural strength, and density.

Table 1: Mechanical properties of aerogels, 3D-Printed Concrete, and metamaterials

Material	**Compressive strength (MPa)**	**Flexural strength (MPa)**	**Density (kg/m^3)**	**References**
Aerogels	0.01–0.5	Very low	3–350	Thapliyal et al. (2014) [2]; Fickler et al. (2015) [13]
3D-printed concrete	40–100	4–6	2200–2400	Wangler et al. (2016); Tay et al. (2017) [27]
Metamaterials	Design-dependent (0.1–100)	Variable	50–5000 (depending on unit cell)	Li et al. (2021) [28]; Ma et al. (2018) [29]

Aerogels, due to their nanoporous structure and extremely low density, exhibit very poor structural performance. Their compressive strength is typically below 1 MPa, making them unsuitable for any structural or load-bearing roles in construction [2]. While there are experimental improvements through polymer-reinforced aerogels, their use remains confined to non-structural applications, such as insulation or cladding.

In contrast, 3D-printed concrete exhibits compressive strength values comparable to or even exceeding those of conventional concrete. Studies by Wangler et al. (2016) and Tay et al. (2017) [27] report compressive strengths ranging from 40 to 100 MPa, depending on the mix design and curing conditions. Although its flexural strength is generally lower, it remains sufficient for small to medium-scale structural applications.

The strength of metamaterials is largely determined by their unique geometric configurations at the microscale. Experimental studies have reported compressive strengths ranging from only a few megapascals to over 100 MPa, depending on the material composition and unit-cell design [28][29]. However, most metamaterials remain at the experimental stage and have yet to be adopted in large-scale construction applications.

4.2. Thermal Insulation

Thermal conductivity is a primary indicator of a material's insulation capabilities. A lower thermal conductivity means better insulation, leading to reduced energy consumption for heating and cooling in buildings.

Table 2: Thermal conductivity of the materials

Material	**Thermal Conductivity (W/m·K)**	**References**
Aerogels	0.013–0.020	Thapliyal et al. (2014) [2]; Illera et al. (2018) [12]
3D-printed concrete	0.3–0.5	Tay et al. (2017) [27]; Wolfs et al. (2019) [30]
Metamaterials	Adjustable (0.02–0.15)	Li et al. (2021) [28]; Wang et al. (2024) [31]; Ma et al. (2018) [29]

Aerogels are regarded as one of the best thermal insulators among known solid materials, with thermal conductivities as low as 0.013 W/m·K [2].

3D-printed concrete does not provide strong thermal insulation, with conductivities ranging from 0.3–0.5 W/m·K [30]. However, thermal performance can be improved by incorporating insulating aggregates or internal voids designed during the printing process.

Thermal metamaterials offer a novel advantage: adjustability. By changing structural geometry, researchers have demonstrated materials that can act as thermal cloaks or concentrators, achieving variable conductivities within the 0.02–0.15 W/m·K range [28][31]. Although promising, such materials are not yet available for large-scale construction.

4.3. Environmental Impact

Evaluating environmental performance involves considering CO_2 emissions, energy usage, recyclability, and life-cycle efficiency.

Table 3: Environmental characteristics

Material	**CO_2 Emissions (kg CO_2/kg)**	**Sustainability factors**	**References**
Aerogels	1.5–2.5	High energy cost but long-term energy savings	Jia et al. (2024) [11]; Thapliyal et al. (2014) [2]
3D-printed concrete	∼0.9	Reduces waste, formwork, and labor; uses recycled aggregates	Tay et al. (2017) [27]; Wolfs et al. (2019) [30]
Metamaterials	Variable (0.5–5.0)	Highly dependent on base materials and production energy	Li et al. (2021) [28]; Ma et al. (2018) [29]; Wang et al. (2024) [31]

Aerogels require significant energy to produce due to the supercritical drying process, but they can greatly reduce operational energy use in buildings due to superior insulation [11]. Their sustainability depends on the life cycle energy balance, which is often favorable in cold or hot climates.

3D-printed concrete is more environmentally friendly because it uses automation, which reduces waste, construction time, and the need for labor [27]. Using materials like recycled aggregates or fly ash in the mix makes it a greener alternative to traditional concrete.

Metamaterials' environmental impact varies widely depending on composition. Polymer-based systems have relatively high carbon footprints. However, since these materials are designed to use small amounts of actual material by controlling their structure at the micro-level, they might end up using fewer resources [28].

4.4. Cost and Scalability

Cost plays a critical role in material adoption. It includes raw material prices, processing, and scalability for construction.

Table 4: Estimated material costs

Material	**Cost (\$/m^2)**	**Cost causes**	**References**
Aerogels	\$100–\$300	Supercritical drying, low production volume	Fickler et al. (2015) [13]; Jia et al. (2024) [11]
3D-printed concrete	\$80–\$120	Equipment setup offset by labor/material savings	Wolfs et al. (2019) [30]; Tay et al. (2017) [27]
Metamaterials	\$200–\$1000	Complex fabrication, limited industrial scaling	Wang et al. (2024) [31]; Ma et al. (2018) [29]; Li et al. (2021) [28]

Aerogels remain highly expensive due to complex production methods and low manufacturing volume. Their production requires special equipment like supercritical drying systems, which increases the cost. Even though prices might drop in the future as the technology improves and becomes more widespread, for now, aerogels are mostly used in specific, high-performance situations where their insulation benefits outweigh the cost.

Although the initial setup cost of 3D-printed concrete can be high due to the need for specialized equipment and materials, it can lead to long-term savings by reducing labor requirements, construction time, and material waste. As the technology continues to mature and become more accessible, it presents a promising solution for large-scale construction projects focused on efficiency and sustainability.

Metamaterials, on the other hand, remain highly expensive because they often require custom design and fabrication using precise laboratory manufacturing techniques. At present, they are not yet practical for use in conventional construction and are primarily limited to research and experimental applications. However, as production methods improve and costs decrease, metamaterials could play a significant role in future structural and seismic engineering solutions.

4.5. Construction Feasibility

This includes how easily the material can be used in real-world construction, considering handling, regulation, and installation logistics.

Table 5: Construction characteristics

Material	**Construction complexity**	**Handling**	**Application status**	**References**
Aerogels	High	Fragile, needs encapsulation	Not yet standardized	Fickler et al. (2015) [13]; Illera et al. (2018) [12]
3D-printed concrete	Moderate	Automated, reduced formwork	Increasing adoption	Tay et al. (2017) [27]; Wolfs et al. (2019) [30]
Metamaterials	Very High	Requires precision equipment	Experimental stage	Li et al. (2021) [28]; Wang et al. (2024) [31]

Aerogels are extremely difficult to handle because of their brittleness. They require specialized encapsulation and are sensitive to moisture unless treated. This significantly increases labor and installation costs [13].

3D-printed concrete has demonstrated impressive construction feasibility, with automated machines capable of producing entire walls and components with little human help. Several projects around the world have already shown successful use.

Metamaterials are still in the research stage. Some small uses, like thermal control panels or sound absorbers, are possible; however, they are not yet ready for widespread construction.

4.6. Durability and Lifespan

Durability is essential for long-term performance. It includes moisture resistance, thermal stability, UV stability, and resistance to mechanical wear.

Table 6: Construction characteristics

Material	**Lifespan (Years)**	**Moisture Resistance**	**UV Resistance**	**Resistance to mechanical wear**	**References**
Aerogels	30–50	Poor unless coated	Good (silica)	Poor	Thapliyal et al. (2014) [2]; Illera et al. (2018) [12]
3D-printed concrete	75–100	Excellent	Excellent	High	Tay et al. (2017) [27]; Wolfs et al. (2019) [30]
Metamaterials	Unknown	Design-dependent	Design-dependent	Unknown	Li et al. (2021) [28]; Ma et al. (2018) [29]; Wang et al. (2024) [31]

Aerogels have a moderate lifespan but are extremely susceptible to mechanical damage and moisture, unless properly sealed. This reduces their viability in exposed environments.

3D-printed concrete shows strong long-term performance. Its resilience to water, weather, fire, and mechanical forces makes it an excellent candidate for robust infrastructure.

The long-term durability of metamaterials remains unknown due to their novelty and lack of standardized long-term testing.

5 Results and Discussion

The comparison of aerogels, metamaterials, and 3D-printed concrete (3DPC) highlights that each material offers distinct advantages suited to different aspects of modern construction. Among the three, 3DPC demonstrates the most balanced combination of structural performance, cost efficiency, and practical applicability. With compressive strengths ranging from 40 to 100 MPa, 3DPC performs on par with or better than conventional concrete while offering additional benefits such as greater design flexibility and faster, more efficient construction. The technology has advanced beyond the experimental stage, as demonstrated by successful full-scale implementations, including the Milestone housing project and pedestrian bridges in the Netherlands. These real-world examples indicate that 3DPC is ready for broader adoption, particularly in projects emphasizing automation and material efficiency.

Aerogels, by contrast, are more specialized materials primarily valued for their exceptional thermal insulation performance. With thermal conductivities as low as 0.013–0.020 W/(m·K), aerogels provide highly effective insulation in thin layers, making them ideal for enhancing building energy performance. However, their fragility and high production cost restrict widespread use, limiting them to applications where superior insulation justifies the expense. Emerging developments such as bio-based aerogels and simplified drying techniques show promise for lowering costs and improving durability, but further progress is required before aerogels can achieve large-scale market adoption.

Metamaterials represent the most innovative yet least technologically mature. Engineered to manipulate the propagation of mechanical vibrations and waves, they exhibit strong potential for seismic protection and blast mitigation. Laboratory studies have demonstrated that metamaterials can reduce vibration energy by up to 80% and improve blast energy absorption by approximately 35%. Despite these promising results, the absence of standardized fabrication methods and limited real-world validation currently restricts their use to research and small-scale applications. In the long term, continued advances in manufacturing precision and cost reduction could enable metamaterials to play an important role in high-performance or hazard-resistant structures where functionality takes precedence over cost.

6 Conclusion

This comparative analysis demonstrates that emerging construction materials offer complementary solutions to the evolving demands of sustainable and high-performance construction. Rather than identifying a single superior material, the study emphasizes that the optimal choice depends on project-specific goals, balancing structural performance, environmental impact, and cost.

3D-printed concrete appears to be the most ready for large-scale application. It provides sufficient strength for structural use and offers major advantages such as faster construction, reduced labor requirements, and lower material waste. As the technology continues to advance, particularly through the development of environmentally friendly mix designs and improved process control, it is likely to become an increasingly versatile solution across a wide range of construction projects.

Aerogels and metamaterials, while currently more specialized, address critical challenges that traditional materials cannot solve. Aerogels already provide reliable, energy-efficient insulation, though high production costs continue to limit widespread use. Metamaterials show strong potential to enhance building safety, especially in mitigating earthquake and blast effects, but further research and large-scale testing are required before practical implementation.

Future research should focus on three priorities: (1) integrating these materials to combine their complementary strengths, e.g., 3D-printed concrete for structure, aerogels for insulation, and metamaterials for protection; (2) improving the cost-effectiveness and scalability of aerogel and metamaterial production; and (3) developing standardized design and safety frameworks for their reliable implementation. As the industry faces growing demands for sustainability, resilience, and efficiency, these advanced materials are positioned to play a central role in shaping the next generation of the built environment.

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