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Review Article

Innovative Lightweight Foamed Concrete Applications for Eco-friendly Green Building Construction

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Md Azree Othuman Mydin[*,1]

[1] Department of Building Surveying, School of Housing, Building and Planning, Universiti Sains Malaysia, Penang, Malaysia

[*] **Correspondence email:** azree@usm.my

Abstract

The construction industry significantly impacts the environment, contributing to energy consumption, material waste, and carbon emissions. As eco-friendly building practices gain importance, sustainable materials like foamed concrete become critical. This lightweight material offers superior thermal and acoustic properties and is an innovative solution for green building construction. Foamed concrete is made by introducing a foam agent into a cement slurry, creating a lightweight material with enhanced thermal insulation, fire resistance, and acoustic attenuation. Its applications in construction include external walls, roofs, partitioning, and insulating concrete formwork (ICF) systems. The lightweight nature of foamed concrete reduces the need for heavy structural materials, enabling resource-efficient designs and minimizing the strain on foundations. Foamed concrete can help achieve green building certifications like LEED and BREEAM. Its high thermal insulation performance reduces heating and cooling energy needs, while its acoustic and fire-resistant properties improve comfort and safety. Despite its advantages, foamed concrete faces challenges such as material consistency, durability, and higher initial costs. Ongoing research aims to address these limitations and develop innovations like recycled aggregates and cost-effective production methods. Case studies and recent advancements highlight foamed concrete's potential to transform building practices towards more sustainable and energy-efficient methods.

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1. Introduction

The demand for sustainable building materials is rapidly increasing as the construction industry continues to contribute to environmental degradation. In response, green building practices have become a focal point in reducing carbon footprints, improving energy efficiency, and conserving resources [1]. Foamed concrete (FC), a lightweight, aerated concrete, has emerged as a promising material for eco-friendly construction due to its advantageous properties, such as energy efficiency, thermal insulation, and low environmental impact. This literature review synthesizes the research on foamed concrete's role in green building construction, exploring its properties, benefits, applications, and the challenges associated with its widespread adoption. Foamed concrete is a form of lightweight concrete that is produced by introducing a foam agent into a cement-based mixture, forming a highly porous structure. The foam is typically generated using synthetic or protein-based agents mixed with air, producing bubbles that reduce the overall density of the material [2]. This modification offers several advantages over traditional concrete, such as improved thermal insulation, reduced weight, and enhanced workability. In green buildings, foamed concrete has garnered attention for its potential to contribute to energy-efficient construction and sustainable development. The composition of foamed concrete typically consists of cement, fine aggregates (such as sand), water, and a foaming agent. The primary difference between foamed concrete and traditional concrete is the introduction of foam, which creates air voids throughout the material. These air pockets reduce the density of the material, improving its thermal properties and making it suitable for various applications in green building construction. Several studies have explored the optimal mix designs for foamed concrete, focusing on balancing strength, insulation properties, and workability. Fig. 1 shows some of the properties of foamed concrete.

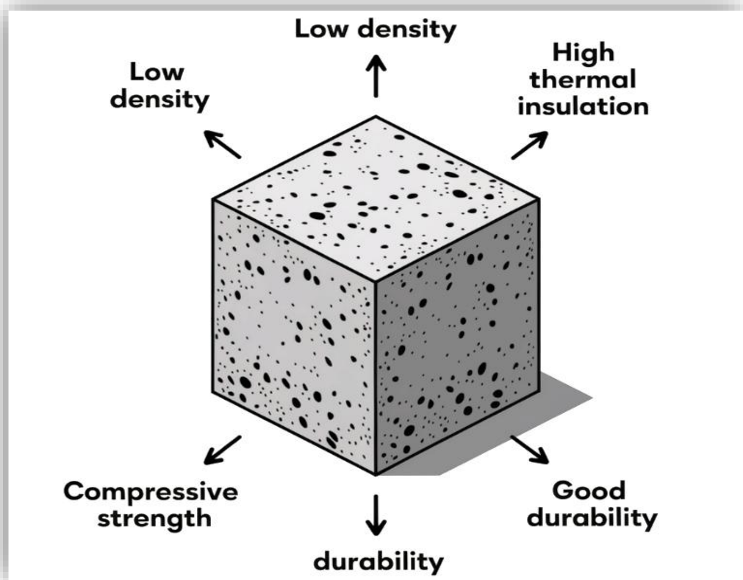

Fig. 1: Properties of foamed concrete.

One of the primary advantages of foamed concrete is its excellent thermal insulation properties. The air voids in the material significantly reduce heat transfer, making it an ideal solution for building envelopes such as walls, roofs, and floors. In buildings, reducing heat loss in winter and minimizing heat gain in summer can lead to substantial energy savings, which are critical for meeting the energy efficiency standards set by green building certification systems like LEED and BREEAM [3]. Foamed concrete can reduce the need for additional insulation materials, offering an integrated solution that lowers a building's operational energy consumption. Several studies have confirmed the thermal efficiency of foamed concrete in different applications. For instance, research by Suhaili et al. [4] demonstrated that foamed concrete with a density of 800 kg/m³ exhibited a thermal conductivity of approximately 0.2 W/mK, lower than conventional concrete by a significant margin. Such reductions in thermal conductivity translate into lower heating and cooling requirements for buildings, which contributes directly to reduced carbon emissions over the lifespan of a building. Another key property of foamed concrete is its reduced weight, which makes it an attractive option for use in non-load-bearing elements like partitions, infill walls, and cladding. The reduction in weight leads to lower demands on the building's foundation and structural system, resulting in reduced material usage and construction costs. Moreover, the lightweight nature of foamed concrete can minimize transportation costs and energy consumption associated with moving heavy materials [4].

Several studies have examined using foamed concrete in non-load-bearing and structural elements. The application of foamed concrete in the construction of internal partition walls was found to reduce the overall dead load of the building by up to 30% compared to traditional concrete. This reduction in dead load decreases material consumption and improves the overall efficiency of the building's structural design. Foamed concrete also provides excellent acoustic insulation properties due to its porous structure. The material is effective in soundproofing, making it suitable for residential, commercial, and industrial buildings where noise reduction is a priority. Several studies have highlighted foamed concrete's ability to reduce sound transmission, with some demonstrating noise reduction values (STC ratings) that meet or exceed the requirements for soundproofing in building codes. Additionally, foamed concrete offers fire-resistant properties, as air voids make it less combustible and able to withstand higher temperatures than normal concrete. The fire resistance of foamed concrete has been documented in various studies, indicating its potential for use in fireproofing structural elements, such as walls, ceilings, and floors [5]. This quality is crucial for buildings aiming for high levels of safety and durability in their design. Foamed concrete is increasingly used to construct exterior walls and façades in green buildings due to its thermal insulation properties and reduced weight. The material's ability to provide a high degree of thermal resistance means that it can reduce the need for additional insulation layers, such as rigid foam boards, further contributing to the sustainability of the building. Furthermore, foamed concrete's lightweight nature reduces the carbon footprint of transporting and installing heavy materials [6]. Foamed concrete is also being used in green roofs, which serve as a lightweight substrate for vegetation. Green roofs provide several environmental benefits, including improved air quality, reduced stormwater runoff, and mitigation of the urban heat island effect. By incorporating foamed concrete in the construction of green roofs, developers can reduce the system's overall weight while enhancing its thermal performance [7].

Insulating concrete formwork (ICF) is a construction technique that involves using foam blocks to form the shape of walls, which are then filled with concrete to create a highly insulated structure. Foamed concrete can be used in this method to provide enhanced thermal insulation, reducing the need for separate insulation materials. ICF systems are particularly beneficial in residential buildings and low-energy homes, where energy conservation is a primary concern. Foamed concrete is also used in floor systems, particularly in applications where reducing the overall weight of the building is a concern. The material's lightweight nature allows it to be used for floor slabs, reducing the foundation's load and lowering construction costs [8]. Additionally, foamed concrete's insulating properties help improve the thermal comfort of the building and reduce energy use. Despite its many advantages, there are several challenges to the widespread adoption of foamed concrete in green building construction. One of the primary challenges is the material's variability, which the quality of the foam agent, mix proportions, and curing conditions can influence. This variability can affect the material's strength, durability, and thermal insulation properties [9].

Another challenge is the higher initial cost of foamed concrete than traditional concrete. While the material offers significant long-term energy savings and reduced maintenance costs, the initial production cost can be a barrier to adoption, especially in markets with budget constraints [10]. Finally, the long-term durability of foamed concrete in harsh environmental conditions is still a topic of ongoing research. Studies have shown that foamed concrete can be vulnerable to moisture absorption and freeze-thaw damage, which may limit its application in certain climates. Researchers are actively investigating methods to improve the material's durability by using alternative curing techniques and incorporating additives to enhance its resistance to environmental factors. Research into foamed concrete is ongoing, with significant advancements in material development and production methods. The use of recycled aggregates and industrial by-products, such as fly ash or slag, has been explored to reduce the material's environmental impact further [11]. Additionally, advancements in foam generation technology and the development of more efficient curing methods are expected to improve the consistency and performance of foamed concrete. Future innovations in foamed concrete may also involve integrating smart technologies, such as temperature sensors or energy-harvesting systems, to create "intelligent" building materials that adapt to changing environmental conditions and improve energy efficiency.

2. Thermal Insulation Performance

One of the most prominent benefits of foamed concrete in green building applications is its superior thermal insulation properties. Several experimental studies have demonstrated that foamed concrete significantly reduces heat transfer compared to traditional concrete. For instance, a survey by Roslan et al. [12] assessed the thermal conductivity of foamed concrete with varying densities (from 600 kg/m³ to 1,200 kg/m³). The results indicated that foamed concrete with a density of 800 kg/m³ exhibited a thermal conductivity of approximately 0.25 W/m·K, nearly half the thermal conductivity of conventional concrete (0.50 W/m·K). This reduced thermal conductivity directly contributes to improved building energy efficiency. Maglad et al. [13] analyzed the energy savings in buildings using foamed concrete for external walls and compared them with traditional concrete. The results showed that the foamed concrete structure required 15% less energy for cooling during the summer and 20% less energy for heating during the winter. The thermal efficiency of foamed concrete makes it a valuable material for sustainable buildings, where reducing energy consumption is a key objective. Its insulating properties reduce the need for additional insulation layers, such as foam boards or fiberglass, leading to simpler and more cost-effective construction methods, as shown in Fig. 2 [14]. Moreover, the superior thermal performance of foamed concrete aligns well with global energy efficiency goals, such as the Paris Agreement's target of reducing carbon emissions from the built environment [7]. However, the thermal insulation performance is highly dependent on the density of the foamed concrete. While low-density foamed concrete offers excellent thermal resistance, it may have reduced compressive strength, which could limit its application in load-bearing structural elements. Optimizing mix designs to balance these competing requirements and high thermal insulation with adequate structural integrity remains an ongoing area of research [15].

3. Acoustic Insulation Properties

Foamed concrete's porous structure gives it notable soundproofing abilities, making it an ideal material for acoustic insulation. The results revealed that foamed concrete with a density of 800 kg/m³ achieved an STC rating of 48, which is above the minimum requirement for noise reduction in residential buildings (STC ≥ 45). In comparison, conventional concrete typically achieves an STC rating of around 45. Additionally, research by Mydin et al. [16] demonstrated the efficacy of foamed concrete in multi-residential buildings, where it was used as an internal partition wall material. The study found that foamed concrete reduced sound transmission between rooms by up to 30%, significantly improving occupant comfort. The ability of foamed concrete to reduce sound transmission makes it a highly suitable material for applications in residential, commercial, and mixed-use buildings, where noise control is a priority. In urban areas, where noise pollution is a growing concern, the use of foamed concrete can enhance the quality of life for building occupants, contributing to healthier indoor environments [17]. The impact of foamed concrete on acoustic insulation, however, is influenced by several factors, including its density, thickness, and mix design. While lower-density foamed concrete provides superior sound insulation, it may not meet structural load-bearing requirements in certain building elements. Therefore, balancing acoustic performance with structural strength is essential for effective application in noise-sensitive environments [18].

Fig. 2: Insulating properties reduce the need for additional insulation layers, such as foam boards or fiberglass.

4. Fire Resistance and Safety

Foamed concrete's inherent fire-resistant properties are another major advantage, particularly in buildings where fire safety is a key concern. The material maintained its integrity under fire exposure, offering enhanced protection compared to traditional concrete. In addition to fire resistance, foamed concrete's low thermal conductivity reduces heat transfer during fire situations, providing additional time for evacuation and firefighting efforts, as shown in Fig. 3. The material effectively contained heat within the affected area, reducing fire spread to adjacent spaces [19]. The fire resistance of foamed concrete positions is suitable for fireproofing structural elements in eco-friendly buildings. With fire regulations becoming increasingly stringent in many parts of the world, using fire-resistant materials is critical in green building design. Foamed concrete's performance in fire safety can lead to reduced dependency on additional fireproofing treatments, such as fire-resistant coatings, which further enhances the material's environmental benefits. However, the fire resistance of foamed concrete can be influenced by factors such as density and curing time. Higher-density foamed concrete may exhibit better fire performance but could also reduce the material's thermal insulation properties. Therefore, achieving an optimal balance between fire resistance and insulation is essential for maximizing the material's benefits in fire-prone areas [20].

Fig. 3: Foamed concrete has low thermal conductivity, which reduces heat transfer during fire situations.

5. Environmental Impact and Sustainability

The environmental advantages of foamed concrete lie primarily in its reduced material usage, energy consumption during production, and the potential for recycling waste materials. Several studies have examined the carbon footprint of foamed concrete compared to traditional concrete. A survey by Mydin et al. [21] used life cycle assessment (LCA) methodology to compare foamed concrete's and conventional concrete's environmental impact in constructing a mid-rise building. The results showed that foamed concrete resulted in a 15% reduction in carbon emissions and a 12% decrease in the energy required for material production. Additionally, foamed concrete's ability to incorporate industrial by-products, such as fly ash or slag, further enhances its sustainability. The lower environmental impact of foamed concrete is one of its key selling points in the context of green building construction. Using recycled materials and reducing energy consumption during production, foamed concrete helps mitigate the environmental challenges associated with traditional concrete production. This aligns with the growing demand for building materials that are functional, sustainable, and resource-efficient. However, the ecological benefits of foamed concrete depend on the sources of raw materials and the production methods used. Using renewable or industrial waste materials, such as recycled aggregates or fly ash, can significantly enhance the sustainability of foamed concrete. Additionally, advancements in foam generation and curing technology can further reduce the carbon footprint of foamed concrete.

6. Cost Considerations and Economic Feasibility

The economic feasibility of foamed concrete in green building applications remains a topic of debate, with concerns regarding the higher initial cost of production than conventional concrete. Furthermore, the lightweight nature of foamed concrete leads to reduced transportation and labor costs, as it can be easily handled and installed. In a case study on constructing a residential building using foamed concrete, Nensok et al. [22] found that the overall construction cost was 7% lower than that of buildings using traditional concrete due to the reduced material handling and lower transportation expenses. While the initial production cost of foamed concrete may be higher than that of conventional concrete, its long-term economic benefits, such as energy savings and reduced maintenance, make it an attractive option for sustainable construction. In regions with high energy costs or incentives for green building certification, the return on investment for using foamed concrete can be significant. Additionally, the lightweight nature of foamed concrete leads to reduced transportation and handling costs, making it more cost-competitive in large-scale construction projects. However, further efforts to reduce production costs, including using locally sourced foam agents and recycled aggregates, will be necessary for the material to gain wider adoption.

7. Challenges in Adoption and Future Research

One of the key challenges in adopting foamed concrete on a large scale is ensuring the consistency of material properties. Variations in foam quality, mix design, and curing conditions can lead to significant differences in the material's strength, thermal performance, and durability. Further research is needed to standardize the production process and improve quality control. The durability of foamed concrete, particularly in extreme weather conditions or in applications subject to moisture and freeze-thaw cycles, remains [23].

8. Conclusion

Foamed concrete presents a promising solution for advancing sustainable construction practices, offering numerous advantages that align with the goals of eco-friendly green building. As the global construction industry faces increasing pressure to reduce its environmental impact, foamed concrete's unique properties—such as superior thermal insulation, acoustic attenuation, fire resistance, and reduced environmental footprint—position it as a key material for energy-efficient and resource-conserving building projects. The material's lightweight nature contributes to structural efficiency, reducing the load on foundations and transportation costs while improving energy performance. Its exceptional thermal insulation properties enhance building energy efficiency, reducing heating and cooling requirements and, consequently, lowering operational energy consumption. Additionally, foamed concrete's capacity to incorporate recycled materials, such as fly ash or slag, further elevates its sustainability by reducing reliance on virgin raw materials and minimizing construction waste. However, despite these compelling benefits, the widespread adoption of foamed concrete in green building applications is challenging. Variability in material properties, such as strength and durability, remains a concern, especially in load-bearing or exposed applications. Furthermore, while the long-term economic benefits of foamed concrete, including reduced energy costs and lower transportation expenses, may outweigh the initial investment, the material's higher production costs still pose a barrier for some construction industry sectors. Future research is essential to address these challenges and unlock the full potential of foamed concrete. Continued innovation in mix designs, production methods, and using locally sourced or recycled foam agents can help improve material consistency and reduce production costs. Furthermore, long-term studies on the durability of foamed concrete in varying environmental conditions will be crucial to ensuring its robustness and longevity in real-world applications. In conclusion, foamed concrete offers a transformative opportunity for the construction industry to embrace sustainability in building design and construction. Its use in eco-friendly green buildings not only enhances energy efficiency and occupant comfort but also contributes to a broader effort to mitigate the environmental impact of the built environment. By overcoming existing challenges and capitalizing on ongoing technological advancements, foamed concrete can significantly shape the future of sustainable construction practices.

Declaration of Conflict of Interest

The authors declared no conflict of interest with any other party on the publication of the current work.

ORCID

Md Azree Othuman Mydin https://orcid.org/0000-0001-8639-1089

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