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A Review on Sustainable Lightweight Foamed Concrete

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ABSTRACT

Addressing the environmental challenges posed by conventional construction materials has become a priority, leading to the exploration of sustainable alternatives. Lightweight foamed concrete (LFC) stands out as a viable option due to its advantageous properties, such as low density, thermal and acoustic insulation, and reduced environmental impact. This review examines the progress made in the development of LFC, focusing on its composition, production processes, and performance characteristics, with an emphasis on its potential for promoting sustainable construction. The study delves into the role of supplementary cementitious materials (SCMs), including fly ash, silica fume, and ground granulated blast furnace slag, in minimizing dependence on ordinary Portland cement and reducing carbon emissions. Additionally, it explores the use of alternative fine aggregates and the refinement of foaming techniques, which collectively enhance LFC's mechanical and thermal attributes. The effects of various production parameters on key properties such as workability, porosity, compressive strength, and thermal conductivity are also analyzed. The review identifies existing challenges, including the relatively lower mechanical strength of LFC compared to traditional concrete and the necessity for meticulous control over its composition and curing processes to ensure consistent performance. Emerging solutions, such as the integration of nanomaterials, innovative foaming agents, and customized curing strategies, are highlighted as promising directions for future research. This paper consolidates recent findings to emphasize LFC’s potential as a sustainable and adaptable construction material. It highlights its practical applications, ongoing challenges, and opportunities for innovation, demonstrating its capability to reduce the construction industry’s environmental footprint while meeting modern performance standards.

1. Introduction

The construction sector has faced growing criticism in recent years due to its significant role in resource depletion and greenhouse gas emissions. As the push for sustainable practices intensifies, both governments and industries are seeking innovative materials that combine environmental friendliness with high performance. Lightweight foamed concrete (LFC) has emerged as a leading contender in this pursuit, offering solutions that align with sustainability goals while delivering practical benefits. With distinctive attributes such as low density, thermal insulation, and excellent workability, LFC is becoming an essential component of eco-conscious construction methodologies.

At its core, LFC is defined by a cellular structure created through the incorporation of stable air voids within a cement-based matrix. These voids not only reduce its overall weight but also enhance its thermal and acoustic insulation properties. The material's versatility allows it to be tailored for a wide range of applications, including thermal insulation layers, partitions, and lightweight fill materials. Moreover, its reduced weight simplifies transportation and lessens the structural load on foundations, contributing to both environmental and cost savings.

A key aspect of LFC's appeal is its potential to support sustainable construction. By incorporating supplementary cementitious materials (SCMs), the need for ordinary Portland cement (OPC)—a major contributor to CO_2 emissions—can be significantly reduced. These SCMs not only lower the carbon footprint but also enhance the concrete's durability and mechanical properties through microstructural improvements. The adoption of industrial by-products as alternative fine aggregates further advances resource efficiency by aligning with circular economy principles and reducing waste.

The production of LFC adds to its sustainability profile by forgoing the use of coarse aggregates and instead relying on fine materials and foaming agents to achieve its characteristic cellular structure. Techniques like pre-foaming and mixed foaming provide flexibility in production, enabling manufacturers to adjust the material's density and strength to suit specific applications. LFC's range of densities, spanning from ultra-lightweight (100–300 kg/m^3) to medium-density (800–1200 kg/m^3), broadens its usability across various construction scenarios.

Despite its advantages, the widespread adoption of LFC is not without challenges. Issues such as lower compressive and flexural strength compared to traditional concrete require ongoing research to optimize its formulation and microstructural control. Additionally, although LFC's lightweight properties reduce the material volume required, this characteristic can lead to higher emissions per unit of strength, emphasizing the importance of innovative design and curing methods. Advances in nanomaterials, specialized additives, and alternative foaming agents offer promising pathways to overcome these limitations and expand the scope of LFC applications.

This paper presents a detailed review of lightweight foamed concrete, focusing on its sustainability-driven development. Topics covered include material composition, production techniques, mechanical and thermal performance, and environmental impact. The study also examines recent innovations such as the integration of SCMs and advanced foaming technologies, highlighting their influence on LFC's microstructure and functionality. By consolidating current research, this review aims to emphasize LFC's transformative potential in sustainable construction while identifying critical areas for future exploration.

2. Fabrication Process of Lightweight Foamed Concrete

To develop foam concrete many different materials can be used, in which the important ingredients are cement and fine aggregate. The following steps are part of the process as shown in Figure 1 : The design framework for HPFC[1] i) First, the binder materials are combined for one minute; ii) Water and superplasticizer (SP) are added, and the mixture is blended for four to five minutes until a slurry forms; iii) A physical foaming machine is used to create air foam by adding a foaming agent; iv) The foam is then combined with the fresh paste for two minutes; v) The HPFC mixture is cast into various molds and left in chamber at 20°C for twenty-four hours; vi) Following the 24-hour period, the samples are demolded and moved to a standard curing chamber with relative humidity more than 90%) for a curing[1].

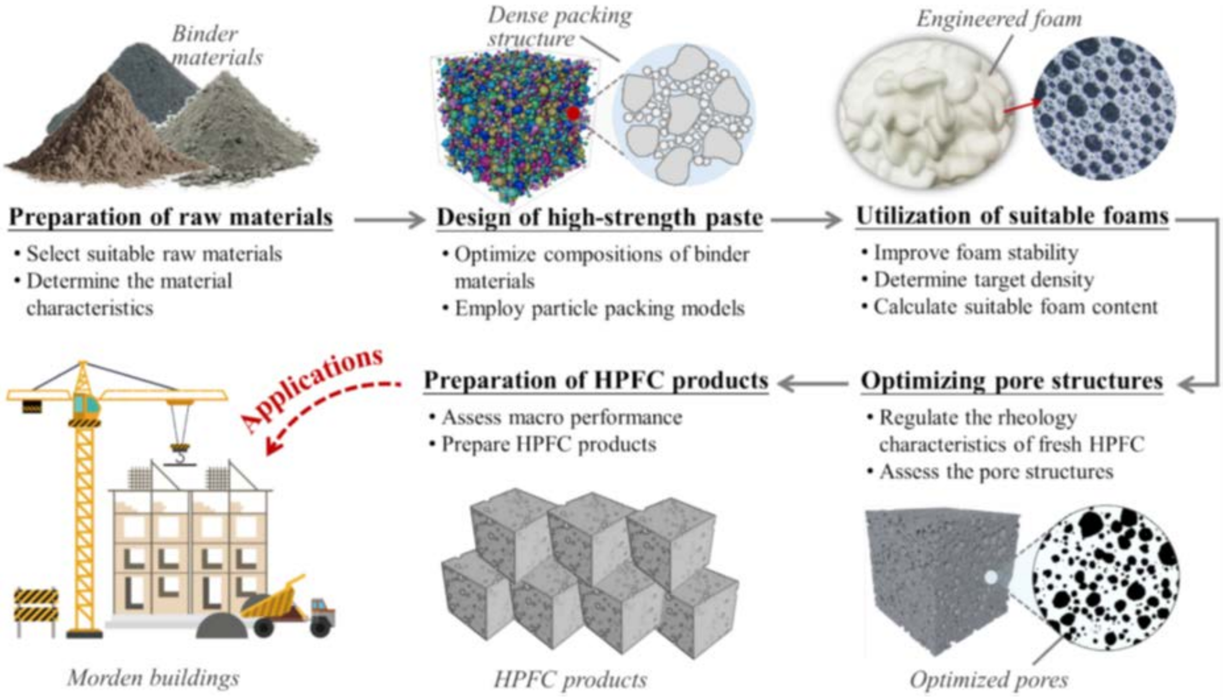

Fig. 1: The design framework for HPFC [1]

3. Constituent Materials of Lightweight Foamed Concrete

To develop foam concrete many different materials can be used as shown in Figure 2: Materials for foam concrete.

3.1. Binder

To enhance early strength and reduce setting time in foam concrete, alternative binders like calcium sulfoaluminate cement, high alumina cement, alkali-activated cement, and rapid-hardening Portland cement are used alongside ordinary Portland cement. Geopolymer cement, made from alkali-activated aluminosilicate binders, offers a more sustainable option, with lower energy consumption and CO2 emissions, while also providing superior fire resistance[2]. To reduce the heat of hydration, SCM materials are used to partially substitute cement (10-75% by weight)[3]. These replacements improve durable strength and flowability, despite delaying the attainment of maximum strength, due to their microfilming effects [4].

3.2. Aggregate

The manufacturing of foam concrete usually excludes coarse particles. The use of alternate fine materials in place of conventional sand in the mix has been the subject of several research.

Fig. 2: Materials for foam concrete

3.3. Foam

Both the pre-foaming and mixed foaming processes may be used to create foam, which is a necessary ingredient of foam concrete. While the foaming agent is introduced precisely to the mixture during mixing in the mixed process, mixture and foam are produced independently and then combined in the pre-foaming technique. Hydrogen peroxide, calcium hydride, and aluminum powder are common foaming agents; smaller particles increase foam production while decreasing concrete density. It is better to use coarse aluminum powder to prevent dust explosions. Although longer mixing durations increase air entrainment, segregation may result from decreased bubble stability. Other elements that affect foam stability include proteins, polymers, and surfactants. Compared to synthetic agents, which work well for medium-density foams, protein-based foaming agents, which are utilized for lower-density concrete, often produce smaller, more stable bubbles and have better compressive strength[5].

3.4. Water demand

Water with a pH around 7, is used. W/C ratio of 0.4 is required to prevent the cement from drawing water out of the foam [6]. A low ratio causes a stiff mix that can break bubbles, while a higher ratio weakens the mix and leads to segregation. A recommended water-to-cement ratio range is 0.4 to 1.25 to avoid water absorption from the foam [7]. The water should be clean and free from contaminants such as oils, acids, and salts, according to ACI 523.3R-93.

4. Fresh Properties

4.1. Flow behavior

Mixtures were developed with small bulk mass in which the voids exceed the particles, leading to pores that affect workability properties. The bubbles, due to thinner walls, are closer together and have sufficient surface charges to appeal each other, leading in a less density [8].

The workability of the mix with densities of around 250 kg/m³ was measured. Despite this, these mixtures could be easily poured and flowed smoothly over a scoop with minimal external assistance to achieve a flat surface[9]. Replacing fine aggregates with coarse fly ash significantly improved the flow properties of mixtures at a density of 1000 kg/m³. In contrast, substituting Portland cement (PC) with fly ash reduced the flowability of flowable concrete (FC) at the same density, as the larger specific surface area required additional water, limiting the effective free water available. The study also explored the impact of using fly ash (FA2) on the flowing characteristics of around 250 kg/m³ mixtures, testing various proportions of FA2 at 30%, to 50% of the PC, despite the noted flowability reduction with fine fly ash.

4.2 Workabilit*y*

The workability of foam concrete is typically evaluated by its viscosity, as the standard slump test is unsuitable for low-density foam concrete. [10] Ideal spread values range up to 125 mm for sand-cement mixtures and 115 to 140 mm for fly ash mixtures. As foam volume increases, the mixture becomes stiffer and requires more water to preserve flowability. Quarry dust mixes show better flowability at lower water-to-solid percentages [10] .

5. Hardened Properties

5.1. Porosity

Foamed concrete's porosity is essential to its functionality, particularly in terms of density and thermal insulation. Porosity was greatly increased by enlarging the foam content to 30%; however, increases over 30% resulted in pore merging because of inadequate cement slurry, which diminished the porosity gains. Furthermore, it was discovered that a greater water-to-cement ratio enlarges porosity, which resulted in increased water absorption but decreased dry density and compressive strength. They discovered that the pore structure was enhanced by altering the foam content, the water to cement ratio, and the use of S80W, a lightweight polymer. Although many holes remained equal in size and unconnected, It was observed that porosity decreases as density increases because bigger pores emerge[11]. The porosity increased with increasing matrix content, rising 5% to each 10% enlargement in the mix. Nano voids also had a role in the total increase in porosity[12].

5.2. Compressive strength

By adding foam to the concrete mixture, ultra-density foam concrete (ULFC) is produced, a special kind of material that is lightweight and porous. The kind and volume of foam utilized, the size and type of aggregates, the w/c, the curing conditions, and the use of supplemental elements like fibers and mixes are few of the changeable that influence ULFC's compressive strength.

Studies have revealed that ULFC with dry densities to 300 kg/m³ exhibit variable compressive strength results. A compressive strength up to 1.05 MPa was observed[11] . Compressive strengths ranging from 0.33 to 1.1 MPa were found for dry densities of 150 to 300 kg/m³][13]. The amount of fly ash in the mix affected the strengths, which ranged from roughly 0.15 to 0.65 MPa at a dry density of 290 kg/m³. Furthermore, compressive values of around 0.1 MPa at 200 kg/m³ and 0.18 MPa at 300 kg/m³ were measured [14]. Increasing river sediment content from 30% to 70% led to a gradual reduction in compressive strength, from 3.87 to 2.23 MPa. River sediment plays a smaller role in the strength of foamed concrete (FC), although reactive alumina and silica found in metakaolin are the main contributors[15]. With compressive strengths after 28 days ranging from 2.3 to 3.9 MPa and dry densities between 222.3 and 252.7 kg/m³, FC made with river sediment nonetheless demonstrated strengths larger than traditional clean-clayey FC, indicating the potential of river sediment in FC applications. A study investigating the effect of expanded polystyrene (EPS) on the mechanical properties of foam concrete (FC) found that increasing EPS content significantly reduced compressive strength. EPS particles are highly compressible and contribute little to the structural strength of FC, leading to a decrease in compressive strength to just 46.32% of the strength observed in specimens without EPS when the EPS mass ratio was 1.0. Additionally, when metakaolin was substituted, the compressive strength of ultra-lightweight foam concrete (ULFC) dropped from 3.87 MPa to 2.23 MPa. However, when river sediment was included at a ratio of 30 to 70%, it was found that the strength of the FC was mainly influenced by the reactive properties of metakaolin, with river sediment having only a minor effect on strength enhancement. Despite this, the FC produced in this scenario was notably stronger than existing clean-clayey materials.

The compressive strength of ultra-lightweight foam concrete (ULFC) at various curing temperatures and ages was investigated[16]. They discovered that while strength climbed with curing time, strength decreased with increasing temperature, dropping by 16% when the casting temperature was 37°C. Cement hydration slowed after 28 days, limiting additional strength increases, while curing gains were noted as time rose from 28 to 90 days. The effects of foam content and (W/C) ratio on ULFC properties were examined[17]. Larger holes were produced by higher foam concentrations, which greatly decreased compressive strength. Because of increased porosity, increasing the W/C ratio also reduced strength. They also examined S80W, a lightweight material, but discovered that the compressive strength of ULFC dropped as its content rose.

Due of its large specific surface area, which helped fill voids and strengthen the matrix, it was discovered that adding (SF) to FC raised its compressive strength[18]. Similarly, it was discovered that, depending on the curing conditions, adding SF with smaller particle sizes could boost strength by as much as 225%[19]. Furthermore, it was found that by better dispersing air bubbles, increasing mixing intensity increased strength and decreased the need for further additives[19].

By minimizing air spaces, it was demonstrated that increased mixing intensity decreased the size of foam bubbles, enhancing mechanical strength[20]. Last but not least, it was assessed six distinct combinations and observed differences in compressive strength[21]. At the water-to-cementitious material ratio, foaming temperature, and hydrogen peroxide (H_2O_2) addition as parameters that affect the compressive strength of ultra-lightweight foam concrete (ULFC)[22]. Up to an ideal ratio of 0.55, they discovered that increasing the water-to-cementitious material ratio increased strength; beyond that, strength decreased. Strength was increased by temperatures of foams up to 45°C, but decreased by higher temperatures. Compressive strength decreased with H_2O_2 addition, especially at densities between 250 and 300 kg/m³. At higher H_2O_2 concentrations, strength fell below 0.25 MPa.

The effect of density and bentonite powder (PB) on the compressive strength of lightweight expanded polystyrene (EPS) concrete was investigated. In combinations with lower densities (300 and 400 kg/m2), PB decreased strength; nevertheless, in mixtures with higher densities (500 and 600. A significant factor was the microstructure, with more porous structures resulting from greater PB doses. After 28 days, PB's pozzolanic action helped to increase strength, especially in combinations that contained more PB.

There was a significant positive connection between compressive and flexural strength, meaning that flexural strength rose as compressive strength did[15].

5.3. Flexural strength

The usage of ULFC in several structural systems is frequently limited by its flexural strength. Flexural strength decreased as river sediment content increased because of the sediment's low activity[15]. Furthermore, the flexural strength was further decreased by the addition of EPS particles.

The effects of polypropylene microfibers and protein-based foaming agents (P1 and P2) on ULFC were investigated[21]. The fibers created a three-dimensional network that improved the mix's overall performance, workability, and stability. Additionally, ULFC P1 F and P2 F attained 61% and 74% of their maximum flexural strength, respectively, according to the flexural strength tests.

The effects of EPS content and river sediment replacement on ULFC's sorptivity and water absorption[15]. Due to decreased compactness, they found that greater substitution of river sediment improved sorptivity and water absorption. In a similar vein, larger EPS content led to higher water absorption because the hydrophobic properties of EPS particles enhanced the impermeability of the concrete. High water absorption may compromise the foam concrete's durability[23].

5.4. Ultrasound pulse velocity

Ultra-lightweight foam concrete (ULFC) qualities, especially strength and durability, have been assessed more frequently recently using the ultrasound pulse velocity (UPV) method[23].

The use of UPV testing to evaluate the sound isolating abilities of foam concrete (FC) was investigated [15].The reduction of river silt and EPS levels in the FC resulted in a considerable rise in UPV readings. Additionally, it was shown that compressive strength and ultrasonic pulse velocity were directly correlated, with lesser porosity being associated with higher UPV. It was discovered that metakaolin was especially useful for increasing FC's internal compactness.

6. Thermal Properties

6.1. Thermal conductivity

Increasing the EPS content in foamed concrete (FC) significantly reduced its thermal conductivity (TC), with reductions of up to 79.1% compared to the control group[15]. The addition of river sediment also reduced TC, but only up to a 30% substitution rate. TC was observed to increase with temperature, although EPS particles reduced TC by about 66.9% under varying conditions. Studies comparing 28% and 82% EPS content revealed that the lower EPS content had 2.5 times higher TC (0.0848 W/(m•K)).

The impact of foam content and water-to-cement (W/C) ratio on ULFC properties was studied[17]. As foam content increased (10%, 30%, and 50%), porosity also increased, leading to a decrease in TC values, from 0.1221 to 0.0647 W/(m•K). They also noted that TC decreased as both porosity and W/C ratio increased. Additionally, the inclusion of HPMC improved thermal insulation by increasing closed porosity, which enhanced heat resistance. Adding S80W reduced TC, but excessive amounts (over 9.5%) lowered compressive strength. An optimal S80W content of 6.5% produced favorable results in density.

SF-substituted FCs exhibited better heat permeability than non-substituted FCs under the same conditions[18]. The TC of ULFC increased linearly with apparent density, with a sample density of 102 kg/m³ demonstrating a low TC of 0.043 W/m·K, similar to materials like mineral wool[22].

7. Carbon Emission

7.1. Developing insulation concrete

Foam insulation concrete is made by mixing cement, water, and a foaming agent, creating a lightweight and insulating material. The process begins with combining the foaming agent, water, and air to generate stable foam. Next, sand and cement are mixed with water to form a mortar slurry, with water added gradually while stirring. The foam is produced by adding water to the foaming agent, which is then extracted using an air compressor and foam generator. This foam is incorporated into the moist slurry and mixed thoroughly. The wet density of the resulting foamed concrete is then checked against specifications. No chemical reactions occur during this process, as porosity is created mechanically through pre-foaming or mix foaming [24]. Foam concrete is widely used in construction for its thermal and acoustic insulation properties.

7.2. Sustainable concrete

The production of foam insulation concrete generates significant greenhouse gas emissions, mainly due to the cement manufacturing process, which involves energy consumption and calcination, contributing to 0.2–0.5 metric tons of CO2 per cubic meter of traditional concrete[25]. Foam concrete's lower density results in reduced cement usage per volume, potentially lowering CO2 emissions. However, the Portland cement used is responsible for approximately 94% of the CO2 emissions, with metakaolin contributing 2.4% and the energy required for foam production having a minimal impact on Global Warming Potential (GWP).

Compared to other industries, foam concrete's emissions are relatively small. It was found that 1 cubic meter of foam concrete produces 508 kg of CO2 equivalent, primarily due to the use of Ordinary Portland Cement (OPC). As the proportion of supplementary materials increases, the environmental impact decreases. Cement production is energy-intensive and relies on fossil fuels, making OPC the primary environmental concern. Substituting cement with other materials can reduce environmental impacts, including global warming potential and ozone layer depletion[26]. However, foam concrete generally leads to higher emissions in all environmental categories [27] .Although foam concrete has small evolution, its effect per unit strength may be higher due to its small compressive strength compared to traditional concrete, and increasing cement content would increase CO2 emissions.

8. Pore Structure and Microstructure

The incorporation of Fly Ash (FA) and Slag (SF) has a notable impact on the pore structure of foamed concrete. It was suggested that the use of a ternary cementitious system combining SF and FA to enhance the void structure of foamed concrete[28]. Similarly, It was utilized that the micro-aggregate and pozzolanic properties of SCM to develop a pozzolanic cementitious foam (PCF)[29]. This combination improved the porosity and pore structure, which in turn influenced the mechanical and thermal properties. It was developed an ultra-stable foam for PCF by combining organic surfactants with nanoparticles[30]. Their matrix consisted of 30 wt.% FA and 10 wt.% SF with Portland Cement (PC). They also demonstrated that the pozzolanic reaction between active silica and Ca(OH)2 produced C-S-H gel, which enhanced the densification of the cell wall structure. The high reactivity and effective filling properties of wet-ground FA boosted the specific compressive strength of PCF by 74%[31].

9. Acoustic Properties

The density, sound frequency, and internal resistance of foam concrete all affect the transmission loss (TL) of airborne sound. Particularly at low frequencies (40–150 Hz), foam concrete provides superior acoustic absorption over ordinary concrete; nevertheless, absorption is more sensitive to material thickness. Fly ash had minimal impact on low-frequency sound, but it enhanced absorption at higher frequencies (800–1600 Hz). The material became more successful at absorbing middle frequencies (600–1000 Hz) when the foam percentage was increased from 5–10%, but less effective at lower frequencies. At low frequencies, thin specimens of geopolymer foam concrete (20–25 mm) demonstrated considerable absorption. Although its closed pore structure reduced sound absorption despite high porosity, studies on foamed cellular concrete with densities ranging to 700 kg/m³ showed better absorption coefficients in lower-density samples[32].

10. Conclusions

Lightweight foamed concrete (LFC) has emerged as a transformative material in the pursuit of sustainable construction solutions. Its low density, excellent thermal and acoustic insulation, and flexibility in application make it a viable alternative to conventional materials. The integration of supplementary cementitious materials (SCMs), such as fly ash, silica fume, and ground granulated blast furnace slag, has proven effective in reducing reliance on ordinary Portland cement, thus lowering carbon emissions. Furthermore, the utilization of alternative fine aggregates and advancements in foaming techniques have enhanced the mechanical and thermal properties of LFC while supporting resource efficiency and waste reduction.

Despite these advancements, LFC faces challenges that need to be addressed for its broader adoption. Key areas include improving its compressive and flexural strength and ensuring consistent performance through optimized formulations and curing methods. Innovations such as nanomaterial additives, advanced foaming agents, and tailored production strategies provide promising avenues for overcoming these barriers.

This review consolidates current knowledge on LFC, highlighting its potential to reduce the environmental impact of construction while meeting modern performance demands. By addressing existing limitations and leveraging emerging technologies, LFC can play a pivotal role in the transition toward environmentally responsible and economically viable building practices. As research progresses, LFC is well-positioned to contribute significantly to the development of sustainable, resilient, and innovative construction systems that align with global sustainability goals.

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