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Challenges in Foamed Concrete: exploring alternative and sustainable materials – A Comprehensive Review

Retos en el Concreto Celular: explorando materiales alternativos y sostenibles – Una revisión integral

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Abstract

This comprehensive review provides an in-depth exploration of foamed concrete, covering various dimensions of its production, properties, and sustainability considerations. The discussion commences with a broad overview of foamed concrete, delving into its typical constituents, including aggregates, water/cement ratio, foam agents, additives, and fibers. The subsequent examination of physic-mechanical properties encompasses critical factors such as compressive strength, flexural strengths, shrinkage, and workability, offering a comprehensive understanding of foamed concrete's performance metrics.

As sustainability emerges as a pivotal theme, the document navigates through diverse strategies employed in foamed concrete production. It investigates the integration of alternative binders and the replacements of aggregates, presenting a holistic approach towards reducing environmental impact. The review further dissects sustainable practices within the realm of foamed concrete, including a meticulous exploration of lifecycle assessment and carbon footprint considerations, embodied energy aspects, insulation behavior, and the durability of the material. By synthesizing information from various sources, this abstract provides a comprehensive overview of foamed concrete, ensuring a well-rounded understanding of its composition, properties, and sustainability implications.

Keywords: Foamed concrete, Lightweight concrete, Alternative binders, Fine aggregate substitutes, Life Cycle Assessment.

Resumen

Esta revisión proporciona una exploración en profundidad del concreto celular, cubriendo varias dimensiones de su producción, propiedades y consideraciones de sostenibilidad. La discusión comienza con una visión general del concreto celular, profundizando en sus constituyentes típicos, incluyendo los agregados (áridos), la relación agua/cemento, los agentes espumantes, los aditivos y las fibras. El examen posterior de las propiedades físico-mecánicas abarca factores críticos como la resistencia a la compresión, la resistencia a la flexión, la retracción y la trabajabilidad, ofreciendo una comprensión global de las métricas de rendimiento del hormigón espumado. A medida que la sostenibilidad emerge como un tema fundamental, este documento navega a través de diversas estrategias empleadas en la producción del concreto celular. Investiga la integración de cementantes alternativos y la sustitución de agregados, presentando un enfoque holístico para reducir el impacto medioambiental. La revisión incluye además las prácticas sostenibles dentro del ámbito del concreto celular, incluyendo una exploración de la evaluación del ciclo de vida y las consideraciones de la huella de carbono, los aspectos de la energía incorporada, el comportamiento del aislamiento y la durabilidad del material. Al sintetizar información procedente de diversas fuentes, este resumen proporciona una visión global del concreto celular, garantizando una comprensión completa de su composición, propiedades e implicaciones para la sostenibilidad.

Palabras clave: Concreto Celular, Concreto Ligero, Materiales Cementicios Alternativos, Agregados Finos Substitutos, Ciclo de vida.

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Introduction

Concrete, a blend of hydraulic cement, aggregates, water, and potential additives, encompasses specific low-density variants, referring to those with a density below the standard 2270 kg/m^3 (1). As defined by the American Concrete Institute (ACI), there are two main types of lightweight concrete. Structural lightweight concrete exhibits an air-dry density not exceeding 115 lb/ft^3 (1,850 kg/m^3) and a 28-day compressive strength surpassing 2,500 psi (17.2 MPa). On the other hand, lightweight concrete, with a low-density characteristic, boasts an oven-dry density below 50 lb/ft^3 (800 kg/m^3), achieved through the incorporation of lightweight aggregates or foaming agents. This category includes foamed concrete, aerated concrete, and sand-lightweight concrete. ACI further characterizes cellular concrete as a low-density product with a homogeneous void or cell structure, achieved using gas-forming chemicals or foaming agents, sometimes undergoing autoclave curing (2–6). This material, as highlighted in the article published by Valore et al. (2) in 1954, has gained significant attention for its ability to entrap air-voids in the mortar using appropriate foaming agents or incorporating voids through chemical agents. As a result, foam concrete exhibits high flowability, low self-weight, reduced aggregate consumption, controlled low strength, and remarkable thermal insulation properties. Despite being patented in 1923, the exploration of foam concrete's potential is currently continuing to evolve and expand (2).

Indeed, lowering paste density in lightweight concrete involves various methods: preformed foam(7–16), mechanical mixing (17,18), and chemical reaction (19). Mechanical incorporates voids through mixer blades at specific speeds in the presence of a foaming agent. The chemical reaction method creates bubbles via specific foaming agents. The preformed foam approach generates foam with a machine, subsequently mixed with mortar, commonly used for producing foamed concrete with reduced densities, offering advantages like foam stability, measurable half-life, and controlled density (8,15,19–22).

Moreover, the drive towards achieving sustainability in lightweight concrete has prompted extensive research into greener alternatives for materials. Investigating alternative materials to replace traditional components is a key aspect of sustainable lightweight concrete development. Researchers have delved into options such as recycled aggregates (23–26), quarry dust (27,28), recycled powders (1,14,29,30), and industrial byproducts (31–35) as viable substitutes while maintaining structural integrity and performance.

In summary, this article comprehensively examines various aspects of foamed concrete, including alternative binders, replacement aggregates, foam agents, and a comparison of mechanical properties. Serving as a valuable reference for practical research, it also explores into emerging sustainability trends in chapter four hat have the potential to significantly enhance foamed concrete production. This contribution aligns with the broader goal of promoting environmentally-friendly and efficient construction practices.

General information about foamed concrete

Foamed concrete is a unique construction material that consists of various constituent materials, including cementitious materials, aggregates, additives and foamed agent. These materials play a crucial role in determining the properties and performance of the foamed concrete (36,37). There are many studies aimed at providing guidelines for expected mechanical properties of foamed concrete compared with density and processing (4,38,39). In the same wavelength, others studies focus on compression properties affected by pore construction(8,39–43), which modifies the cementitious matrix and plays a crucial role in dry. In all cases, the binder must hold the components together, and any change determines the material's behavior under service conditions.

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Foamed concrete, renowned for its insulation properties achieved by replacing traditional aggregates with expanded perlite and glass sand, offers enhanced thermal insulation suitable for various applications. This includes addressing challenges in cold regions, such as permafrost areas, where hollow cellular concrete blocks facilitate air convection, as demonstrated through numerical simulations preventing heat transfer from roadways to subbases (11,50,78). Additionally, investigations into lightweight foamed concrete for housing applications in Jordan emphasize the significance of achieving an optimal density for practical and efficient construction (80).

Structural applications of foamed concrete have been researched, achieving compressive strengths greater than 25 MPa, making it viable for structural use (12). Its lower weight compared to ordinary concrete suggests potential applications in seismic areas, offering advantages like increased vibration mode and decreased shear forces in reinforced concrete frames, along with reduced raw material consumption and environmental impact. Moreover, an innovative solution includes a prefabricated light steel solid waste high-strength foam concrete composite wall introduced in a study (69), showcase the material's versatility in achieving load-bearing and energy-efficient integration, demonstrating enhanced bearing capacity, deformation performance, and seismic behavior suitable for earthquake-prone areas. Additionally, studies on the application of Foam Concrete (FC) in the construction of deep-buried structures reveal insights into its dynamic mechanical properties and energy absorption mechanisms, offering potential solutions for challenging construction environments (22).

Typical constituents in foamed concrete production

In the realm of foamed concrete, cement stands as the predominant binder, with various types, including ordinary Portland cement, rapid hardening Portland cement, calcium sulfoaluminate cement, and high alumina cement, being viable choices for formulation (5,10,11,13,14,16). The choice of cement type and its proportion within the mixture depends on the specific application requirements (5). Beyond traditional cement options, other binders have been explored as potential replacements, encompassing fly ash (14–17), ground blast furnace slag (16–18,44–46), electric arc slag (47–50) and Silica Fume (17,18).

While Portland Cement remains the most commonly employed binder, extensive research has delved into alternative replacements to enhance mechanical properties (14,15,22–24,27,34,44,51–54). Evaluating the suitability of ashes as binding materials in lightweight concrete or other applications necessitates a comprehensive examination of their CaO content. This approach ensures a thorough understanding of the diverse binder options available for optimizing foamed concrete formulations.

Aggregates

The choice of fine aggregate in foamed concrete production is crucial for desired properties, enhancing overall workability, mixture cohesion, and facilitating homogeneous distribution of binder and voids. Studies (13,14,43,55) have explored various recycled fine aggregates, foundry sand, and recycled concrete powder (RP) from wastes, to maintain lightweight characteristics. Many of them are used as a supplementary cementitious material. The fineness of aggregates, specifically the maximum sand diameter, proves advantageous in foamed concrete production, achieving densified matrix (12,46). Researchers have also investigated palm oil fuel ash (POFA) as a sand substitute, revealing improvements in residual strength and high-temperature resistance (10).

Experimental investigations involved parameters like weight loss, residual strength, X-ray diffraction (XRD) analysis, thermogravimetric analysis (TGA), differential thermogravimetry (DTG), modulus of elasticity, and failure modes. Additionally, waste clay brick was studied as

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a replacement for coarse aggregate (granite) in foam concrete (56,57). Up to 25% of coarse aggregate could be replaced with waste clay brick (25% and 50%) without significant adverse effects on compressive strength compared to the control sample, as found by researchers..

Studies on fresh densities of 1500 kg/m3 and 1600 kg/m3 in lightweight concrete with preformed foam have been conducted. The first study focused on evaluating concrete performance based on density (9). The second study underscored the importance of achieving a suitable density while preserving desirable mechanical and thermal attributes (11). These research approaches contribute valuable insights for the development of lightweight concrete with optimized properties, showcasing the ongoing efforts to advance the field of foamed concrete through innovative material choices and meticulous experimentation.

Role of water/cement ratio

The performance of foamed concrete is influenced by the critical factor of the water/cement ratio (W/C), which plays a key role in mechanicals properties such as workability, strength, and durability of the material. The influence of different W/C ratios on the properties of foam concrete was examined in various studies (11,13,14,16,18,43,58). This ratio not only impacts compressive strength, thermal conductivity, and porosity but also interacts with replacements influencing foam concrete characteristics (13,14). Moreover, another investigation compared the fresh density and foaming agent dosages with three different W/C ratios: 0.20, 0.30 and 0.40 (18), similar to results from a reduced W/C ratio of 0.33 achieved by incorporating superplasticizers and viscosity-enhancing agents (43). Furthermore, certain authors adopted W/C ratio in constant of 0.45 (11) while others utilized a ratio of 0.50 (10). These researchers shifted their attention towards investigating additional factors that influence the microstructure of foam concrete. Their exploration encompassed aspects like bubble stability and the substitution of aggregates, taking into account factors such as fineness modulus.

Next, the Table 1 present information that underscores the necessity of conducting a thorough analysis to determine the ideal W/C ratio. This ratio holds significant importance, particularly when exploring alternative cementitious materials. Numerous authors have highlighted this factor, underscoring its relevance in achieving favorable results. The strategic incorporation of additives like superplasticizers further adds to the potential for desirable outcomes.

Table 1. Comparative review of water / cement ratio

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Binders	Target dry density	Water/Cement Ratio	Advantages	Disadvantage	Best results	Reference
Porland Cement -Ultra fine Slag	**800kg/ᵐ3**	**0.35**	**Improved flowability**	**Extra milling process for slag**	**Flowability 263mm & Compressive Strength 7.75MPa**	(16)
Porland Cement – Fly Ash	**600kg/m³**	**0.40**	**Achieved low density with a composite protein**	**Foaming agent is expensive**	**Half time foam evolution reached 86min**	(14)
Porland Cement	**1500kg/m³**	**0.45**	**Improved flowability**	**Low compressive strength**	**40% sand replacement by expanded perlite**	(11)
Porland Cement	**1635kg/m³**	**0.50**	**40% Palm Oil Fuel Ash as a Sand Replacement**	**Require Superplasticizer**	**Compressive strength 18MPa**	(9,10)
Porland Cement -Silica Fume – Blast Furnace Slag	**1817kg/m³**	**0.2**	**Mechanical foam formation**	**Require Superplasticizer**	**Compressive strength 48.21 MPa**	(18)
Porland Cement	**100kg/m³**	**0.33**	**Very low density**	**Very low compressive strength 0.22MPa**	**Flowability was not affected by 5% of PP fibers.**	(43)

Foam Agent

The utilization of various foaming agents in foamed concrete production has been investigated in numerous studies (11,13–16). Typically, protein-based molecules form stable foam, often mixed with stabilizers for durability. A unique approach utilized a synthetic surfactant with CH_3 (8). Foam stability was assessed using a beaker, comparing its behavior to a reference sample, and incorporating formic acid for comparison.

Pre-formed foam is widely used in foam concrete production to introduce air-voids, creating lightweight concrete (7,8,10,11,13–16,43). Several foam agents, such as sodium dodecyl sulfate (SDS), stabilized with hydroxypropyl methylcellulose (HMPC) and wet-ground limestone powder, achieved a foam density of 50 kg/m3 using an ultrasonic instrument (16). Plant protein foam agent (PPFA) and enzyme-based protein foaming agents contributed to improved stability and overall performance (11,15).

Chemical foaming agents, including aluminum oxide powder, impact foam concrete properties through gas production (usually carbon dioxide) within the mortar mixture. Sodium hydroxide solution can enhance densification, making foam concrete suitable for structural applications (17). Recycled powder (RP) from waste concrete added to the mixture led to reduced thermal conductivity and improved insulation properties (14).

The foaming process involves a mechanical foaming device or machine to agitate the mortar, incorporating air and generating a foam-like structure. Different dosages of foamed agent (0.3%, 0.6%, and 0.9%) are investigated to stabilize bubbles (18). Other mixing approaches were

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studied, achieving a compressive strength of 101 MPa and 28 MPa with 1620 kg/m3 for the reference and lightweight concrete (18,59,60).

Several studies have focused on enhancing the stability of foam concrete. The effect of formic acid as an accelerator on foam stability, compressive strength, and pore size distribution was investigated (8), the use of formic acid had a positive impact on foam stability, resulting in improved properties of the foam concrete. Additionally, synergy between surfactants and nanoparticles to improve foam stability was explored (19), this research demonstrated the potential for enhancing the stability of foam concrete through this combination. Moreover, stability, flexural behavior, and compressive strength of ultra-lightweight fiber-reinforced foamed concrete with a dry density lower than 100 kg/m3 were examined(43), their findings provided insights into the stability aspects of low-density foam concrete. These studies contribute to the understanding of stability-related factors and techniques for achieving more stable foam concrete structures (8,19,43).

Additives

The impact of additives on foamed concrete properties is significant, as explored in studies utilizing sodium hydroxide solution (17). This solution serves as an alkaline activator, enhancing geopolymers reactions with Silica Fume, reducing porosity, improving compressive strength, and contributing to foam formation and stabilization. Although crucial for achieving desired foamed concrete characteristics, further research is recommended to address shrinkage and efflorescence issues associated with high alkali content in geopolymer concrete.

In the foamed concrete industry, plasticizers are commonly employed to preserve foam bubble stability. Improved rheological properties were demonstrated in the study on polycarboxylate superplasticizer as an additive, enhancing flowability and preventing compaction and vibration that could negatively impact the microstructure (20). Another investigation focused on formic acid as an accelerator in foam concrete production (8). While accelerating cement hydration, increasing compressive strength, and reducing water absorption, the addition of formic acid did impact foam stability.

The compatibility of various materials and additives in foam concrete has been investigated in several studies. To begin with, there was a focus on enhancing compressive strength through the incorporation of ultra-fine slag into the foam concrete mixture (16). Subsequently, a study was conducted to develop alkali-activated foam concrete using fly ash and GGBS (Ground Granulated Blast Furnace Slag), with the aim of exploring the compatibility of these materials(17). Additionally, the physico-mechanical and structural properties of alkali-activated fly ash foam concrete were examined, including the inclusion of Yellow River silt (15). These studies provide insights into the compatibility of different materials and their effects on the overall performance of foam concrete structures (15–17).

Fibers

The incorporation of fibers into foamed concrete has proven to be a significant factor in enhancing mechanical properties, leading to improvements in flexural behavior and compressive strength (43,61–65). Beyond these structural benefits, the inclusion of fibers has also been shown to enhance the overall stability of the material. While existing studies have focused on the positive impact of fiber reinforcement on low tensile strength and strain capacity in foamed concrete (66–69) , further research is highly recommended to explore the effects of different types of fibers on various properties of cellular concrete. This ongoing investigation into fiber types and their diverse effects holds great potential for advancing the understanding and application of fiber-reinforced foamed concrete in construction.

doi: 10.25100/iyc.v25isuplemento.13156

Physic-Mechanical properties

In a separate study, the stability, flexural behavior, and compressive strength of ultra-lightweight fiber-reinforced foamed concrete with an extremely low dry density of 100 kg/m^3 were examined (12,43). Their findings shed light on the structural properties of such lightweight concrete and offer insights into the implications of low density on its overall performance and strength.

Compressive strength

The referenced studies cover a broad spectrum of foam concrete investigations, with a primary focus on enhancing compressive strength. Approaches include the utilization of ultra-fine slag (16), recycled powder (14), alkali-activated foam concrete using fly ash and GGBS (17) or Yellow River silt (15) , and empirical formula modeling for predicting compressive strength (36).

Researchers have explored smart materials and sustainable technologies for concrete construction, potentially influencing compressive strength improvement in foam concrete (70). Other studies focused on sustainable lightweight foam concrete, incorporating palm oil fuel ash as a sand replacement (10) and utilizing expanded perlite and glass sand (11). These investigations typically involved a comprehensive examination of physic-mechanical characteristics, including compressive strength, durability, and insulation properties.

Additional studies assessed compressive strength through the properties of foam concrete with foundry sand and latex (13) and explored the synergy between surfactants and nanoparticles to improve foam stability (19). An influential study (18) emphasized the impact of density on compressive strength in foamed concrete, highlighting that concretes without foam achieve maximum strength. As density decreases, compressive strength also decreases. One study evaluated foamed concrete for structural applications, achieving a compressive strength of 21 MPa at a density of 1,800 kg/m3, comparing it with ultra-high-performance concrete. Remarkably, the same compressive strength of 21 MPa could be attained with ordinary Portland Cement at a density of 2,300 kg/m3.

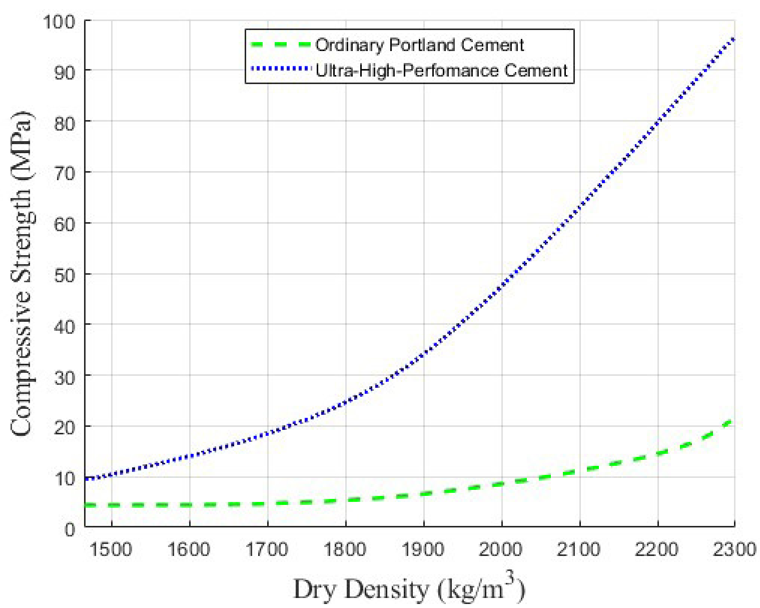

Figure 1. Adapted from Lee H et al. (18)

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Achieving remarkably low densities close to 100kg/m^3 in ultra-lightweight fiber-reinforced foamed concrete demands a comprehensive investigation into its stability, flexural behavior, and compressive strength. The outcomes of such research yielded a compressive strength of 0.3MPa (43). Likewise, a similar emphasis on preparing and characterizing foamed concrete through the use of a foaming agent and locally sourced mineral resources resulted in a compressive strength of 4MPa, coupled with a density of 700kg/m^3 (7).

Based on the compressive strength data illustrated in Figure 1, as depicted in several articles authored by different researchers, it becomes evident that lower mechanical properties are observed when the density is reduced through the pre-foaming method or mechanical aeration. These authors highlight that the introduction of bubbles has a negative impact on the overall behavior of the material, specifically in terms of compressive strength, leading to the occurrence of numerous micro flexural failures.

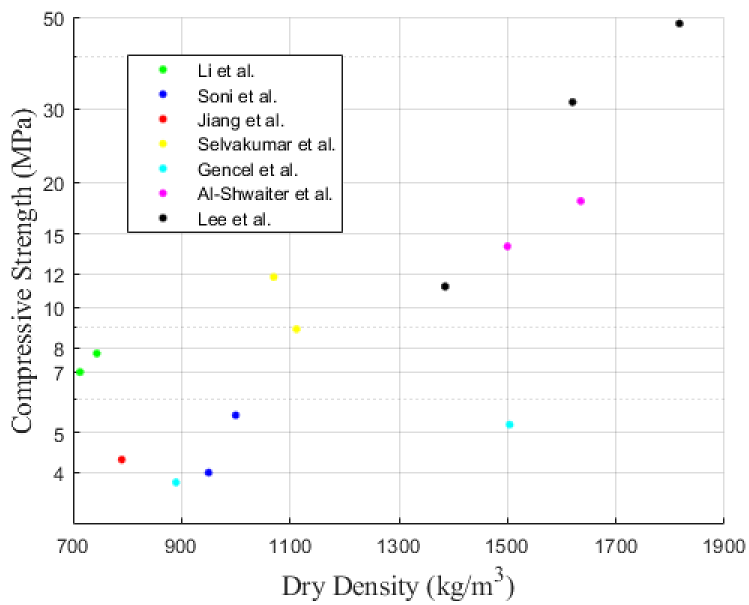

Figure 2. Comparison between dry density and compressive strength

Currently, there is a focus on developing optimized strength modeling methodologies for foamed concrete, utilizing techniques such as principal component analysis featurized regressors, as evidenced by a recent model development (36). An advanced prediction model for the failure mechanism of foamed concrete has been proposed, offering insights into factors influencing compressive strength (71). Considering service conditions, preliminary studies have been conducted on structural foamed concrete for applications in seismic areas, with a likely assessment of compressive strength (12). Additionally, an experimental study explored the seismic behavior of a fabricated lightweight steel solid waste high-strength foam concrete composite (72).

Flexural strengths

The flexural behavior of ultra-lightweight fiber-reinforced foamed concrete were improved in 460% through the addition of polypropylene fibers reaching 0.027MPa with a density of 100kg/m3 (12). Indeed, the addition of admixtures and replacements can significantly enhance the mechanical properties of mortars and concretes. In other study the incorporation of 20%

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sugar cane bagasse ash or 25% rice husk ash as replacements in the mix improved the flexural behavior in 20% (73). However, the replacement of natural aggregates with recycled aggregates in concrete can have an impact on its tensile properties (23). The reason behind this lies in the influence of the hydration process on the bond strength between the mortar and concrete components of the mixture.

Shrinkage

Several authors have emphasized a heightened drying shrinkage in foamed concrete when compared to normal weight concrete (2,5,15,74,75), particularly due to the absence of coarse aggregates, resulting in shrinkage values up to 10 times greater. The introduction of a filler-cement ratio has been identified as a remedy to mitigate this shrinkage behavior. Interestingly, typical scenarios involving the replacement of 40% of sand with fly ash have demonstrated only a marginal impact on shrinkage. The manifestation of shrinkage is intricately linked to foam stability, prompting the use of formic acid as an accelerator in foamed concrete to address this issue. Notably, this additive not only mitigates shrinkage but also enhances pore size distribution (9).

The elevated porosity and increased number of voids in foamed concrete expose a larger surface area to drying, leading to heightened moisture loss during curing. This distinctive structural configuration not only influences properties such as shrinkage but also yields additional benefits, notably improved insulation.

Workability

Several studies have delved into the fluidity characteristics of foam concrete. The investigation into the enhancement of compressive strength in foamed concrete, achieved through the incorporation of ultra-fine slag, prompted considerations of its potential impact on fluidity. Additionally, the exploration of physic-mechanical and structural properties of alkali-activated fly ash foam concrete, incorporating Yellow River silt, likely involved an evaluation of the mixture's fluidity. Collectively, these studies shed light on various aspects of the fluidity of foam concrete, offering valuable insights into its behavior (15–17,60).

The enhanced fluidity in foamed concrete stems from its distinctive air-entrained structure, primarily characterized by stable bubbles distributed throughout the mixture. These air bubbles act as efficient lubricating agents, diminishing internal friction between particles and imparting a heightened level of workability (4,76). The reduced density attributed to the introduced air contributes significantly to the improved fluidity of foamed concrete, allowing for easier movement and settlement into desired forms.

Sustainability in foamed concrete: strategies

Foamed concrete is recognized as a sustainable construction material for multiple compelling reasons. Firstly, the deliberate inclusion of voids in the mixture results in a reduction in the consumption of cement, sand, and water, rendering it an environmentally-friendly choice (21,59,70,77). Secondly, the material boasts exceptional insulation properties, contributing to heightened energy efficiency and reduced heating or cooling requirements in buildings (78,79). Additionally, the lower self-weight of foamed concrete enables the construction of taller structures, facilitates material optimization in foundations, and enhances seismic resistance (80,81). The incorporation of waste materials further enhances sustainability, as these byproducts not only mitigate environmental impact but also offer valuable, low-carbon alternatives that can even improve mechanical properties.

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Alternative binders in foamed concrete

Within the domain of alternative binders, a crucial consideration is the carbon footprint linked to cement production. Notably, Portland Cement emits 1 ton of CO_2 for every ton produced (29,82), highlighting the environmental impact of conventional binders. Studies (14,15,17,18,44–46,48,83–85) have delved into various alternative binders, encompassing fly ash, ground blast furnace slag (GBFS), silica fume (SF), alkali-activated fly ash (AAFA), bottom ash (BA), and the utilization of geopolymer cements derived from slag. These alternative binders present significant potential for advancing sustainable construction practices. Additionally, our discussion will explore the replacement of binders, adjustments to the water/cement ratio, and the incorporation of fibers.

The use of ultra-fine slag (UFS) as a replacement of Portland cement (PC) in a study aiming to enhance compressive strength (16). Results showed increased strength, improved fluidity, and the promotion of a dense microstructure through UFS addition. Similarly, fly ash and ground granulated blast furnace slag were investigated for alkali-activated foam concrete development (17). Incorporating these industrial waste products significantly improved sustainability, with the optimal mixture of fly ash, GGBS, and silica fume exhibiting the highest compressive strength. The use of ultrafine GGBS was suggested for further strength improvement, attributed to geopolymer reactions and CaO contribution from GBFS. Similar findings were reported exploring the use of Yellow River silt (YRS) in AAFA foam concrete (15,83). The foam concrete showed notable properties such as water absorption and pore structure exhibited improvements, while significant strength development was observed over time. This phenomenon was attributed to the formation of C-S-H (calcium-silicate-hydrate) gels, with their characteristics being influenced by the presence of 10% of CaO of the YRS.

To address CaO deficiency in ashes, lime addition is recommended, and early strength cement can enhance binding capacity (25,34). In order to achieve a higher CaO content, the use of early strength cement is recommended, which in turn accelerates the heat-driven hydration process (52,73).

The pursuit of sustainability has prompted a focus on utilizing waste materials, a theme that has garnered considerable attention in recent studies on foamed concrete. Researchers have investigated the integration of diverse waste materials, including fly ash, GGBS, waste glass sand, and Yellow River silt (11,15,17,86). The incorporation of these waste materials as partial replacements in foamed concrete production not only diminishes waste generation but also enhances specific properties of the concrete. Notably, the addition of fly ash and GGBS has been shown to improve the compressive strength and durability of foamed concrete (17,87,88). Furthermore, substituting waste glass sand for lightweight expanded perlite contributes to enhanced physico-mechanical properties, durability, and insulation characteristics of foamed concrete (11).

Studies evaluating the physical properties of agricultural waste, such as palm oil fuel ash and other agricultural ashes, must be processed into fine powder. In the same way as construction and demolition waste, these processes are crucial for enhancing reactivity (1,9,14,24,29,30,53,73). Higher reactivity is exhibited by finer powders, improving mechanical properties and enabling the incorporation of these waste materials into foamed concrete for sustainable construction practices (30,89,90). Several authors (27,35,(91–93)53) have conducted investigations on the use of these ash byproduct as a pozzolanic material in cementitious matrices.

Finally, there is a lack of mention regarding the utilization of ash byproduct from the combustion of agricultural waste as a binder in foamed concrete.

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Replacements of aggregates

Foamed concrete has the potential to repurpose fine particles from diverse waste sources. However, the mere inclusion of these particles does not inherently enhance mechanical properties. Instead, finer particles can uphold and sustain these properties (94). Insights into the potential for utilizing alternative materials such as waste glass sand, fine marble powder, bottom ash, palm oil fuel ash, fine recycled concrete as a replacement in foam concrete (9–11,55,83,95,96). And the properties of foamed concrete were also investigated through the replacement of pulverized sand with foundry sand at various proportions (13).

Sustainable practices in foamed concrete

To counter the unsustainable depletion of natural resources, a global movement advocating for zero waste has emerged as a crucial strategy to address the ongoing environmental crisis. The detrimental impact of Ordinary Portland Cement (OPC) is widely acknowledged, with various studies incorporating recycled aggregates, recycled concrete powder, and construction and demolition waste (1,14,23,25,26,30,53,59,76,97,98).

To further enhance the physical properties of foamed concrete and reduce its environmental impact, the incorporation of supplementary cementitious materials (SCMs) is paramount. SCMs, such as fly ash or slag, not only diminish the carbon footprint associated with traditional cement but also contribute to pozzolanic reactions, thereby improving the overall performance and durability of foamed concrete (10,56,78,79,99).

However, a promising shift towards sustainability lies in the production of geopolymers. This involves aluminosilicates in an alkaline solution, presenting itself as an eco-friendlier alternative within the cement industry (29,31,34,44,54,82,100,101).

Lifecycle assessment and carbon footprint

As previously stated, Portland cement is widely used as a binder in construction, and aggregates are commonly sourced from natural reserves. Nevertheless, lime and cement production contribute to 1% and 8% of the global anthropogenic CO_2 emissions, respectively. (85,102,103). The rate of these CO_2 emissions of can be reduced by using alkali-activated concrete instead of Portland cement as a binder. Studies on emissions from the cradle to the preconstruction were calculated based on Life Cycle Assessment (LCA) details in the literature, achieving a 55% and 80% reduction in carbon footprint (32,44,96,101,102,104–110).

Innovative strategies also involve analyzing the feasibility of sourcing raw materials locally, which not only reduces transportation-related fuel consumption but also aligns with smart logistics practices (105,110). Conducting a life cycle assessment provides a comprehensive evaluation of the environmental impact of foamed concrete throughout its entire life cycle, aiding in the identification of areas for improvement and facilitating informed decisions for sustainable construction practices (105,110). Finally, the utilization of renewable energy sources in the production processes of foamed concrete stands as a significant step towards further reducing the carbon footprint associated with its manufacturing (111).

Embodied energy

Foamed concrete proves to be an effective means for reducing embodied energy (112). By introducing voids into the concrete mixture, foamed concrete achieves decreased weight, thereby reducing the consumption of raw materials, including aggregates and binders. Thorough assessments of embodied energy calculations further emphasize the positive impact of adopting

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foamed concrete in the production of precast panels, highlighting its potential as a sustainable alternative in construction processes. Through these integrated strategies, the construction industry can enhance energy efficiency and advance toward more environmentally conscious and resource-efficient practices.

Reducing the weight of precast panels offers a promising avenue for positively impacting embodied energy (EE) in construction. Research findings indicate that such weight reduction strategies can lead to significant EE savings. For instance, incorporating lightweight materials or optimizing panel designs has been associated with noteworthy reductions in embodied energy compared to conventional construction methods. This general principle underscores the potential for innovative approaches in panel manufacturing and material selection to contribute to more energy-efficient and sustainable construction practices (21,43,106,112).

Insulation behavior

In the pursuit of minimizing energy consumption in buildings, the development of predictive models has emerged as a valuable tool to assess the efficiency of heat and cold management. Extensive research endeavors have been dedicated to exploring energy-saving composite panels and innovative materials characterized by low heat transfer properties, resulting in a noteworthy 17% reduction in heat loss (11,96,113,114).

To optimize the thermal performance of foamed concrete, studies have unveiled that the introduction of voids or air cells plays a pivotal role in enhancing its insulation behavior. The stability of preform foam, coupled with the deliberate incorporation of microbubbles into the concrete matrix, significantly contributes to this improved thermal efficiency (14,40,61,64,107,113). However, it's crucial to note that while these advancements positively impact insulation, they also exert influences on both compressive strength and elastic modulus, underscoring the need for a balanced consideration of multiple factors in the pursuit of energy-efficient construction solutions (60,104,115,116).

Durability

The durability of foamed concrete is intricately linked to the porosity and permeability arising from its inherent pore structure. While acknowledging that its durability may be comparatively reduced when juxtaposed with Portland cement, careful considerations throughout its life cycle become imperative to ensure longevity. Nevertheless, foamed concrete showcases notable strength in diverse aspects, exhibiting resilience against challenges such as resistance to freeze-thaw cycles, elevated temperatures, carbonation, and more (27,47,49,64,117,118). The multifaceted durability profile of foamed concrete underscores its potential as a resilient and reliable construction material, particularly when tailored to address specific environmental conditions and project requirements.

Conclusions

Drawing insights from the discussed articles, a discernible correlation emerges between the dry density and compressive strength in foamed concrete. Notably, there is a consistent trend wherein a decrease in the dry density of foamed concrete corresponds to a decline in compressive strength, especially when compared to control samples lacking foam. This correlation underscores the importance of carefully managing the density-compressive strength balance in foamed concrete formulations.

In the pursuit of sustainable practices and a judicious use of natural resources, the replacement of fine aggregates and exploration of alternative binders stand out as crucial strategies. The choice

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of alternative binders, distinguished by heightened reactivity due to finer particles, is a promising avenue for partially substituting cement. However, it is imperative to implement a systematic substitution plan that evaluates both the fresh and dry state behaviors. Essential tests, including the slump test, shrinkage assessment, compressive strength test, and flexural strength test, serve as critical benchmarks to ensure the feasibility of these sustainable practices.

In the realm of foam, a comprehensive evaluation becomes imperative, encompassing both the self-stability of the foam and the stability of mortar-foam interaction. The incorporation of additives, such as superplasticizers and fibers, is strongly recommended to address potential weaknesses in the structure of foamed concrete, as discussed in this chat. These additives play a pivotal role in enhancing the overall performance and durability of foamed concrete.

Considering a holistic perspective, a life cycle assessment emerges as a valuable methodology for optimizing or reducing raw materials and transforming waste into valuable resources, aligning with the sustainability discussions in this chat. This methodology facilitates a comprehensive comparison of carbon footprint and embodied energy, providing a robust means to validate the sustainability of environmentally friendly products designed with greener practices in mind.

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