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The Application of Foam Concrete in Civil Engineering

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Abstract. Foam concrete, as a porous lightweight material, is widely used in construction, transportation, and geotechnical engineering. Based on a review of relevant literature, this article systematically summarizes the physical and mechanical properties, functional characteristics, and application progress of foam concrete in civil engineering. The study shows that the physical properties of foam concrete have significant tunability, and density, pore size, and ratio are the key factors affecting its strength and durability; in terms of functional characteristics, it performs excellently in insulation, fire resistance, freeze resistance, and energy absorption, especially showing unique advantages in cold regions and seismic engineering. In terms of engineering applications, foam concrete has evolved from a traditional insulation filling material to a composite material with both structural and functional properties, and is widely used in building envelope structures, road subgrades, abutment backfill, and underground linings, etc. With the advancements in material modification technology, carbon dioxide curing, and 3D printing construction technology, foam concrete has great potential for high-performance and green low-carbon development. Future research should focus on optimizing pore structure, strengthening interfaces, and exploring the coupling mechanism of multiple functions to promote its in-depth application and sustainable development in civil engineering.

Keywords: Foam concrete, porous lightweight material, physical and mechanical properties, functional characteristics, civil engineering applications

1. Introduction

Foam concrete is a porous lightweight material formed by mechanically mixing cement slurry with foaming agents. Due to its low density, good insulation properties, and simple construction, it has been widely used in modern civil engineering. Its core feature lies in the uniformly distributed closed bubble structure within it. This microscopic porous system endows the material with excellent lightweight, insulation, and energy absorption properties, making it an important way to achieve building energy conservation and structural lightweighting. Song et al. pointed out that the uniformly distributed closed bubble structure inside foam concrete gives it excellent insulation and sound insulation properties [1], while significantly reducing the structural self-weight, and thus it has been widely applied in walls, roofs, and foundation treatment areas.

Hong et al. believes that foam concrete has the characteristics of being lightweight [2], having a high porosity, and low thermal conductivity, and has obvious advantages in building energy

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conservation, green building materials, and fireproof and heat insulation systems. From the perspective of development history, foam concrete was initially used for non-load-bearing filling and insulation layer construction. With the improvement of foaming technology and the performance of cementitious materials, its mechanical strength and durability have been significantly improved, and its application scope has gradually expanded to structural engineering, transportation engineering, and geotechnical fields. Guo et al. summarized the recent research progress at home and abroad, pointing out that foam concrete is developing from a traditional non-load-bearing insulation material towards a structural composite material [3]. Its application scale in roads, bridges, and underground engineering is continuously expanding. Fan et al. discovered through the design and preparation research of high-strength carbon dioxide foam concrete that introducing carbon dioxide curing and microscopic control technologies can effectively improve the pore size distribution and enhance the interface bonding force, thereby achieving the balance of lightweight and high strength [4]. The emergence of such research indicates the development of foam concrete from a traditional energy-saving material towards a functional and high-performance material.

In recent years, the demand for energy conservation and environmental protection in the construction industry has continuously increased, promoting the performance optimization and process innovation of foam concrete. Researchers have explored in directions such as lightweight structures, green preparation, and composite modification, proposing multiple optimization paths, including using industrial by-products to replace part of the cement, adding fibers or polymer modifications to enhance toughness and crack resistance, and achieving precise control of material morphology through digital construction and 3D printing technology. These technological advancements not only improve the structural uniformity and durability of foam concrete but also provide support for its application in complex engineering environments.

The research and application of foam concrete reflect the trend of multidisciplinary integration in materials science, environmental engineering, and structural engineering. It has significant potential in energy conservation, resource recycling, and improvement of engineering safety, and has become an important direction in the research of new building materials. This article will systematically review the material characteristics and functional performance of foam concrete, analyze the application progress and optimization strategies in different fields of civil engineering, and further explore future development trends, providing references for related research and engineering practice.

2. Properties of foamed concrete

Foamed concrete is a typical porous lightweight material, with its interior filled with closed or semi-closed bubbles, resulting in a density much lower than that of ordinary concrete. Depending on the porosity, its dry density generally ranges from 300 to 1600 kg/m^3, which can be controlled by adjusting the dosage of foaming agent and the mixture ratio. This high porosity structure endows the material with significant lightweight characteristics, giving it outstanding advantages in reducing structural self-weight and improving construction convenience. At the same time, the presence of pores also reduces its overall strength and stiffness, so the design of foamed concrete needs to achieve a balance between lightweight and load-bearing capacity.

From a mechanical perspective, foamed concrete is a typical quasi-crystalline material, and its compressive strength usually increases with density. Experimental studies have shown that the strength increase is closely related to the pore size distribution. When the bubbles are uniform and the pore walls are dense, the compressive and flexural tensile strength can be significantly improved.

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Liu et al.found through dry-wet cycle tests that the formation and expansion of microcracks on the pore walls are the main cause of mechanical performance deterioration, especially under initial damage conditions, the cyclic environment accelerates pore connectivity and structural degradation, showing strong environmental sensitivity [5]. This study indicates that the stability of the pore structure directly affects the durability and service life of the material.

Foamed concrete also has good adjustable properties. Its density, strength, and water absorption rate can be controlled by changing the water-cement ratio, foaming pressure, or type of admixture. Wan et al. found through orthogonal experiments that the introduction of polypropylene fibers can significantly enhance compressive strength and splitting tensile strength within a certain range, forming an internal support network, thereby improving the stress transfer path and delaying brittle failure [6]. When the fiber dosage is moderate, the material achieves better mechanical stability while maintaining a low density.

The deformation performance and stress distribution characteristics of foamed concrete are unique. Due to the presence of a large number of bubbles inside, the material can absorb energy through elastic buckling and local collapse of the pore walls when subjected to pressure, exhibiting certain energy absorption characteristics. Compared to ordinary concrete, its elastic modulus is lower, which can disperse external loads within a small strain range, suitable for non-load-bearing or areas with high adaptability requirements. The study also found that moderate external admixtures such as fly ash or silica fume can enhance the density of the pore walls, reduce capillary pores, and improve impermeability and structural integrity, thereby improving long-term mechanical stability.

Foamed concrete exhibits comprehensive characteristics of light weight, low strength, adjustable properties, energy absorption, and environmental sensitivity in physical and mechanical properties. Its porous structure is both the source of performance advantages and brings limitations in strength and durability. Through reasonable design of pore parameters, optimization of foaming processes, and the use of fiber and mineral admixture composite modification, an effective balance can be achieved between light weight and high strength, laying the foundation for its application in construction, transportation, and geotechnical engineering.

3. Functional properties

Foamed concrete has significant diversity in functional properties, with its unique porous structure providing excellent insulation, heat preservation, fire resistance, freeze resistance, and energy absorption characteristics. As a material with both structural and functional properties, it not only meets the lightweight requirements in construction engineering but also plays an important role in energy conservation and safety performance.

In terms of insulation and heat preservation performance, foamed concrete has an extremely low thermal conductivity, typically ranging from 0.08 to 0.30 W/(m·K). The enclosed bubbles form a large number of air layers, significantly reducing the efficiency of heat transfer. Hong et al.pointed out that the smaller the bubble diameter and the more uniform the distribution, the better the thermal conductivity of the material [2]. This microscopic structural feature makes foamed concrete an ideal building energy-saving material. Compared with traditional insulation mortar, this material has more stable insulation effect, is less prone to attenuation over time, and has good integrity. It can be directly combined with the load-bearing structure to form a composite wall. Foam concrete has a relatively high thermal inertia and can effectively buffer the impact of temperature differences between day and night on the building's enclosure structure, thereby improving indoor thermal comfort and energy efficiency.

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In terms of fire resistance, foam concrete is an inorganic non-flammable material and its fire resistance limit can usually reach more than 3 hours. The material contains a large number of closed bubbles, which can form a heat insulation layer under high-temperature conditions, blocking the transmission of heat and smoke. Studies have shown that it can still maintain a high structural integrity at 1000°C and will not release toxic gases or undergo melting deformation. This characteristic makes it have great potential for application in fireproof partitions, tunnel linings, and fireproof layers of high-rise buildings.

In terms of frost resistance, Gong et al. studied the freeze-thaw damage characteristics of foam concrete using acoustic emission identification technology [7]. It was found that the acoustic emission signal patterns corresponding to different freeze-thaw damage types can be used to monitor the development of internal cracks, providing a new means for durability assessment. Niu S et al.'s review indicated that the frost resistance of foam concrete is closely related to the pore structure morphology [8]. The closed bubbles can provide a buffer space for frost expansion water, reducing the stress concentration caused by ice crystal expansion, and thus delaying the expansion of microcracks caused by freeze-thaw cycles. Especially in cold-region buildings and transportation infrastructure projects, appropriately optimizing the pore diameter distribution and pore wall strength can significantly improve the durability of the material. Fiber composite modification further improves the microcrack propagation path, enabling the material to maintain high structural stability under repeated freeze-thaw conditions.

In terms of energy absorption and earthquake resistance, foam concrete has excellent energy dissipation capacity due to its internal bubble compression characteristics.Research findings demonstrate that through structural design of auxetic foam concrete, lateral contraction and energy absorption can be achieved during compression, significantly enhancing impact resistance and seismic performance.This special structure foam concrete shows application potential in traffic protection facilities, underground engineering, and seismic components.

Foam concrete also has good sound insulation and sound absorption performance. The air layer in the porous structure can effectively attenuate sound wave propagation, especially having a strong absorption effect in the mid-low frequency range, suitable for use in the field of architectural acoustics. Compared with traditional sound-absorbing materials, it has a stable structure, no harmful volatile substances, and a long service life, conforming to the development direction of green building materials.

The functional characteristics of foam concrete stem from its unique microstructure, including bubble morphology, dense pore walls, and composition of the formula, which jointly determine its comprehensive performance in insulation, fire resistance, frost resistance, and energy absorption. Future research can further expand its application boundaries through multi-scale structure regulation and functional admixture technology, enabling it to play a greater role in green buildings, transportation engineering, and protective structures.

4. Application and optimization of foam concrete in civil engineering

As a composite material with both structural and functional properties, foam concrete is increasingly widely used in civil engineering fields such as construction, transportation, geotechnical engineering, and bridges. Its lightweight and porous characteristics give it unique advantages in load reduction of structures, foundation reinforcement, and energy insulation. In recent years, researchers have continuously improved its performance through modification technologies and process optimization, achieving efficient matching between the material and engineering requirements.

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4.1. Construction engineering field

In construction engineering, foam concrete is widely used in exterior wall insulation layers, roof leveling layers, non-load-bearing walls, and floor filling. Its low density and low thermal conductivity enable the building enclosure structure to have excellent energy-saving and insulation performance. Hong et al.pointed out that using foam concrete insulation materials can significantly reduce building energy consumption, improve indoor thermal environment, and reduce the thickness of the exterior wall while increasing space utilization [2]. In prefabricated buildings, foam concrete composite wall panels have gradually become a substitute material for traditional blocks due to their strong integrity, good sound insulation effect, and superior fire resistance.

Furthermore, the requirements for lightweight and construction efficiency in building structures have driven the innovation of foam concrete construction techniques. The maturity of mechanized pumping and on-site foaming technologies has enabled uniform pouring and rapid forming in large-scale construction. To address the problem of the brittleness and low bearing capacity of traditional foam concrete, researchers have introduced fiber reinforcement and polymer modification technologies. Recent research has demonstrated that an optimization model for fiber content and performance, established through response surface methodology, confirms that appropriate control of fiber volume fraction and foaming pressure can simultaneously enhance compressive strength and crack resistance while maintaining lightweight characteristics, offering new technical avenues for structural applications in construction projects.

4.2. Transportation and geotechnical engineering field

In transportation and geotechnical engineering, foam concrete is widely utilized in roadbed filling, soft soil foundation reinforcement, slope stabilization, and pipeline backfilling. Research employing the FLAC3D numerical simulation method has demonstrated that the density stratification of foam concrete significantly influences the stability of existing highway widening structures.The results showed that different density layer configurations could significantly improve the stress distribution of the new and old road bases, reduce differential settlement and foundation additional stress, and thereby enhance the overall stability and service life of the widened road base. This research provided a scientific basis for the rational design and stratified application of foam concrete in transportation infrastructure.

In the field of foundation reinforcement and tunnel backfill, foam concrete also exhibits excellent adaptability. By adjusting density and foaming volume, it can achieve control of foundation deformation and redistribution of soil stress. Lightweight foam concrete can be used as an environmentally friendly filler instead of gravel, for large-scale filling or underground pipe gallery lining, providing sufficient support while avoiding adverse effects of excessive lateral pressure on the structure. The combined use of polypropylene fibers and mineral admixtures can significantly improve the stability of foam concrete in a humid and hot environment, enhancing its anti-seepage and anti-shear performance, and thus extending its service life in road and geotechnical structures.

4.3. Bridges and underground engineering field

In bridge engineering, foam concrete is used in bridge abutment filling, road embankment joints, and void backfilling, etc. Its lightweight property can effectively reduce the structural self-weight and reduce uneven settlement. By controlling density and bubble distribution, good flexural-tensile matching can be achieved, improving the overall coordination between the abutment and the roadbed. For tunnel and underground space engineering, foam concrete is often used as backfill material for lining, to disperse surrounding rock pressure and provide insulation, fire resistance, and anti-seepage functions. Its pumpability and fluidity enable rapid construction in narrow spaces, meeting the filling requirements under complex geological conditions.

In recent years, the development of functionalized foam concrete has further expanded its application in underground and protective structures. By modifying with nanomaterials and designing with negative Poisson's ratio structures, higher energy absorption capacity and impact resistance can be achieved, providing new solutions for underground seismic engineering. Through multi-objective optimization design methods, researchers are attempting to achieve balance among strength, density, energy absorption rate, etc., thereby achieving coordinated optimization of material functions and structural performance.

The application of foam concrete in civil engineering has gradually shifted from traditional insulation and filling functions to structural and functional directions. With the improvement of material modification technologies and numerical simulation methods, the controllability of its performance has significantly increased, providing more design space and innovation paths for construction, transportation, and underground engineering. In the future, the research on foam concrete will further evolve towards high-performance, low-carbonization, and intelligence, providing solid material support for the sustainable development of civil engineering.

5. Conclusion

Foam concrete, as a porous and lightweight composite material, has been continuously studied and applied in civil engineering. Through a systematic analysis of its material properties, functional performance, and engineering practice, it can be seen that this material has broad prospects in areas such as building energy conservation, structural lightweighting, foundation treatment, and protective engineering. Its low density, high porosity, and good thermal insulation properties make it a key component in green building systems, while also demonstrating excellent adaptability and economic efficiency in transportation and geotechnical engineering fields.

From the perspective of material performance, the physical and mechanical properties of foam concrete have significant tunability. By controlling the pore size distribution, density, and foaming process parameters, an optimal balance between lightness and strength can be achieved. Methods such as fiber reinforcement, mineral admixtures, and polymer modification effectively improve its brittleness and durability. Research literature indicates that the rational design of pore structure and reinforcement system is the key direction for improving mechanical properties and extending service life.

In terms of functional performance, foam concrete exhibits excellent thermal insulation, fire resistance, freeze resistance, and energy absorption properties, and is suitable for fire protection layers in high-rise buildings, cold-region roadbeds, and seismic structures. Its inorganic non-flammable characteristics and porous microstructure provide dual guarantees for building safety and energy conservation. Functional research is shifting from traditional insulation materials to multi-performance composite materials. By introducing nanoparticles, phase change materials, and multi-scale structure design, the synergistic optimization of thermal conductivity, strength, and energy absorption performance can be further achieved.

At the engineering application level, the application scope of foam concrete has expanded from a single insulation layer to bearing structures and complex geological environment projects. In the construction field, prefabricated composite wall and roof systems have achieved integrated construction and energy conservation; in transportation and geotechnical engineering, the

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lightweight property is effectively used to reduce foundation loads and control settlement; in bridges and underground engineering, its pumpability and fluidity are adopted to meet the rapid filling requirements under special space conditions. These advancements indicate that foam concrete is transforming from an auxiliary material to a structural-functional integrated material.

Looking to the future, the development direction of foam concrete will be more diversified and intelligent. On one hand, low-carbonization and green production are important trends. Technologies such as carbon dioxide fixation and substitution of cement with industrial by-products can significantly reduce energy consumption and emissions. On the other hand, the introduction of digital design and 3D printing technology will drive breakthroughs in shape control and structural performance prediction for foam concrete. With the continuous integration of materials science and engineering applications, foam concrete is expected to play a greater role in high-performance buildings, transportation infrastructure, and disaster prevention and mitigation.

Foam concrete has become one of the key materials driving the sustainable development of civil engineering. Future research should seek a balance between structural design, material modification, and environmental friendliness, and through interdisciplinary innovation, further enhance material performance and engineering adaptability, providing solid support for achieving green, safe, and efficient civil engineering construction.

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