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Recent Advances in Nano-Modified Foamed Concrete: From Mechanical Properties to Multifunctionality

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Abstract. Foamed concrete is widely used in the construction field due to its light weight and thermal insulation properties. However, its inherent contradiction between strength and porosity results in poor mechanical properties and high brittleness. Nanomaterials, with their small size effect and high reactivity, provide an effective way to break through the above bottlenecks. This paper systematically reviews the influence mechanisms of nanomaterials such as nano-SiO_2, carbon nanotubes and graphene oxide on the mechanical properties, bubble stability and multifunctionality of foamed concrete, focuses on the particle bubble stabilization mechanism based on the Pickering effect, and summarizes the research progress of functionalization such as photocatalytic self-cleaning, electromagnetic shielding and self-healing. Studies show that nanomaterials synergistically improve mechanical strength through filling, pozzolanic reaction and bridging effects, realize bubble stabilization through interfacial adsorption and rheological control, and endow the material with new functions such as environmental purification and electromagnetic protection. At present, there are still challenges such as dispersibility, cost and long-term durability evaluation. In the future, efforts should focus on low-cost dispersion technology and multifunctional collaborative design. This review provides a systematic reference for the high-performance realization and engineering application of foamed concrete.

Keywords: Foamed concrete, Nanomaterials, Mechanical properties, Pickering Bubbles

1. Introduction

Foamed concrete is a porous building material formed by introducing stable bubbles into cement-based paste through physical or chemical foaming processes, which contains a large number of uniformly distributed closed spherical pores inside (usually accounting for 40%~80% by volume) [1]. Its dry bulk density is usually between 300\1600 kg/m³, only 1/4\1/3 of that of ordinary concrete, which can significantly reduce the self-weight of structures and foundation loads. Meanwhile, benefiting from the low thermal conductivity of air, the thermal conductivity of foamed concrete can be as low as 0.06~0.28 W/(m·K), showing excellent thermal insulation performance, making it an ideal material for energy-saving integration of building envelope structures. With good sound insulation, energy absorption, seismic resistance, impact resistance and fire resistance, foamed concrete has been widely used in prefabricated building envelopes, energy-saving roof

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systems, road expansion, underground pipeline backfilling and geotechnical engineering lightweight fillers.

However, as a porous heterogeneous brittle material, foamed concrete still faces significant technical bottlenecks in engineering applications. The core problem lies in the inherent contradiction between strength and porosity: a large number of bubbles introduced for light weight and thermal insulation seriously "dilute" the cement paste matrix, reduce the effective stress area, and make the internal stress field distribution complex, resulting in the common problems of low compressive strength (especially when the density is lower than 1000 kg/m³), low elastic modulus, high brittleness and high sensitivity to early shrinkage and cracking of foamed concrete [2]. In addition, connected pores or pore wall defects often lead to high water absorption, which in turn causes secondary problems such as durability degradation. These limitations restrict foamed concrete to non-load-bearing structures or filling fields at present, making it difficult to achieve large-scale application in load-bearing components.

The rapid development of nanomaterials provides a new path to break through the above technical bottlenecks. Due to their small size effect, high surface energy and high reactivity, these materials can significantly optimize the microstructure of cement matrix, strengthen the interfacial transition zone (ITZ) and refine the pore size distribution even at an extremely low dosage [3]. The strengthening effect of nanomaterials on foamed concrete is essentially a collaborative modification process running through micro to macro scales: at the micro scale, high-activity particles such as nano-SiO_2 and nano-Al_2O_3 generate dense calcium-silicate-hydrate (C-S-H) gel through the dual mechanisms of micro-aggregate filling and pozzolanic reaction, improving the compactness and strength of the matrix while retaining the porous characteristics; at the meso scale, nanomaterials optimize the pore wall-paste interface structure by improving the rheological property of paste and heterogeneous nucleation effect, eliminating the weak links of microcrack initiation; at the macro scale, one-dimensional nanomaterials with high aspect ratio such as carbon nanotubes (CNTs) exert toughening mechanisms such as crack bridging, deflection and fiber pull-out by constructing a three-dimensional network structure, significantly improving the fracture toughness and impact resistance of the material. The progressive collaboration of the three mechanisms jointly builds a multi-scale reinforcement system for high-performance foamed concrete.

Although existing reviews have sorted out the foamed concrete technology and the application principle of nanomaterials in traditional concrete, for the interdisciplinary field of "nano-modified foamed concrete", current researches mostly focus on the verification of the strength of foamed concrete with specific density by a single nanomaterial, lacking a systematic discussion on how different nanomaterials affect bubble stability, rheological properties and long-term durability. In view of the decisive regulatory role of nanomaterials on the microstructure evolution and macro-performance improvement of foamed concrete, it is particularly urgent to systematically sort out the research progress in this field. Writing an in-depth review covering the types, dispersion technologies, action mechanisms and multi-scale performance effects of nanomaterials will not only help clarify the current research status and controversies, but also provide key theoretical support and technical guidance for the development of a new generation of high-strength, low-shrinkage and multifunctional foamed concrete, which has important scientific significance and engineering value for expanding the application of foamed concrete in high-end engineering fields.

2. Application of nanomaterials in foamed concrete

Nanomaterials refer to materials with at least one dimension in the range of 1~100 nm in three-dimensional space, and their physical and chemical properties are completely different from those of

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macroscopic bulk materials, mainly including surface effect, small size effect, quantum size effect and macroscopic quantum tunneling effect [4]. In cement-based composites, nanomaterials are mainly used as high-performance modifiers, and their action mechanisms are highly dependent on chemical composition, geometric shape and microscopic morphology. According to dimensional characteristics, they can be divided into zero-dimensional, one-dimensional and two-dimensional materials; according to chemical properties, they can be divided into inorganic oxides, carbon-based materials and functional semiconductor materials.

Nano metal oxides are the most widely used type of zero-dimensional granular materials. Among them, nano-SiO_2, with its high pozzolanic activity, can react with $Ca(OH)_2$ to generate dense low calcium-silica ratio C-S-H gel, significantly improving the later strength and chloride ion penetration resistance of foamed concrete [5]. Nano-Al_2O_3 particles can act as efficient crystal nuclei to induce the directional growth of hydration products, refine the crystal structure to reduce microcracks, and strengthen the pore wall with its high hardness to reduce the risk of brittle failure [6]. In addition to a certain strengthening effect, nano-TiO_2 can endow the material with environmental purification function due to its photocatalytic activity, degrading organic pollutants and nitrogen oxides under ultraviolet irradiation, providing a possibility for preparing self-cleaning green wall materials [7]. The three materials synergistically promote the development of foamed concrete towards high strength, durability and functionalization through physical filling, chemical reaction and functionalization mechanisms respectively.

Carbon-based nanomaterials show great potential in the field of toughening and strengthening. One-dimensional CNTs are formed by rolling single-layer or multi-layer graphene sheets, with extremely high aspect ratio and tensile strength (up to more than 100 GPa). In the foamed concrete matrix, CNTs act like "micro-bridges", exerting a bridging effect during crack initiation and propagation, effectively inhibiting crack propagation through pull-out energy dissipation and crack deflection mechanisms, and significantly improving fracture toughness and impact resistance [8]. In addition, its excellent electrical conductivity provides a possibility for the development of intelligent sensing materials with piezoresistive effect. The abundant oxygen-containing functional groups on the surface of two-dimensional graphene oxide (GO) endow it with good dispersibility in cement paste, and its huge specific surface area provides a large number of nucleation sites for hydration products, inducing the formation of a denser hydration network structure [9]. The collaborative use of one-dimensional CNTs and two-dimensional GO can significantly improve mechanical properties and expand application prospects such as intelligent sensing and durability protection.

In recent years, the emergence of a number of new nanomaterials has provided more choices for the precise regulation of foamed concrete performance. Janus particles exhibit unique anisotropy due to different chemical compositions or functional groups on their two sides, which can be efficiently adsorbed at the gas-liquid interface and form a dense solid-like membrane, showing significant advantages in the field of particle bubble stabilization technology [10]. Modified hydrophobic nano-SiO_2 endows particles with moderate surface wettability, so that they can not only be efficiently adsorbed at the gas-liquid interface to strengthen the liquid film during bubble stabilization, but also form a good interface bond with cement hydration products, and optimize the uniformity of pore structure and compactness of pore wall at the same time [11]. In addition, nano-ZnO has both semiconductor and piezoelectric properties, which can endow materials with photocatalytic and self-sensing functions; nano-$CaCO_3$, as an efficient nucleating agent, can accelerate early hydration and improve rheological properties; while emerging two-dimensional materials such as MXene and black phosphorus show potential in high-end functional fields such as electromagnetic shielding and intelligent sensing with their unique electrical conductivity and

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layered structure [12]. The continuous development of the above new nanomaterials has opened up a new direction for the construction of a foamed concrete material system with both high strength, low shrinkage and multifunctional collaboration.

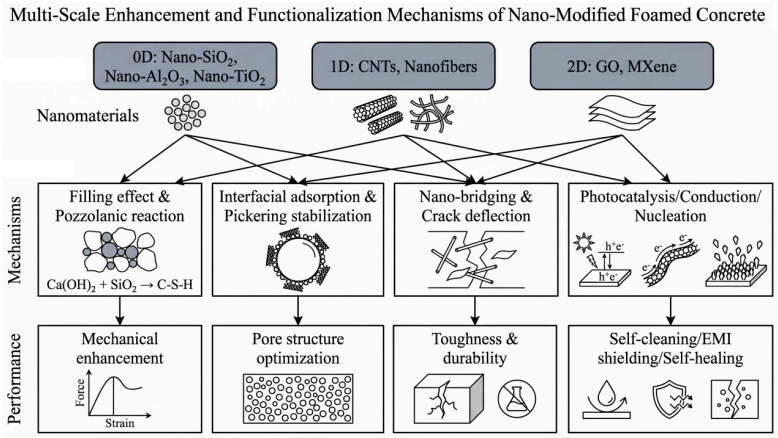


Figure 1. Influence mechanisms of nanomaterials with different dimensions on the performance of foamed concrete

3. Effects of nanomaterials on the properties of foamed concrete

3.1. Effect of nanomaterials on fresh rheological properties of foamed concrete

The fresh rheological properties of foamed concrete (including yield stress, plastic viscosity, etc.) directly affect its bubble stability, casting molding and final mechanical properties. In recent years, nanomaterials represented by nano-SiO_2 (NS), carbon nanotubes (CNTs), nano-TiO_2 (NT), nano-ZrO_2 (NZ) and polymer nanoparticles (PNPs) have been widely introduced into the foamed concrete system, significantly changing its rheological behavior.

NS is the most widely studied nano-modified material due to its high specific surface area and pozzolanic activity. She et al. [11] found that NS and organic surfactants are synergistically adsorbed on the bubble surface, which can increase the paste viscosity, slow down bubble coalescence and disproportionation, and thus obtain a more uniform and fine pore structure. Li et al. [13] systematically studied the effect of NS on the rheological parameters of cement paste through the Herschel-Bulkley model. The results show that with the increase of NS dosage, the minimum viscosity (ηmin) of cement paste first decreases and then increases, while the yield stress (τ_0) continues to increase. Hou et al [14]. further pointed out that an appropriate amount of NS can increase the viscosity of foam liquid with little effect on its surface tension, thus significantly improving the stability of prefabricated foam. However, Turkmenoglu et al. [15] pointed out that the combined use of silica fume and NS can densify the interfacial transition zone, but will significantly reduce the ductility of the paste and increase the rheological resistance.

CNTs have an extremely large aspect ratio and tend to form a network structure in the paste. Studies on the effect of CNTs on the fresh rheological properties of foamed concrete point out that the dispersibility of CNTs and the type of surfactant are the key factors affecting the rheological behavior [16]. The addition of CNTs usually leads to an increase in paste viscosity and yield stress, but the foam stability can be improved through the compounding of appropriate surfactants. Li et al. [17] conducted a rheological study on cement-based composites containing different types of CNTs,

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established a viscosity prediction model, and found that the higher the CNTs dosage, the more significant the shear thickening trend of the paste.

In terms of other nanomaterials, Li et al. [13] compared the effects of three nanoparticles (NS, NT and NZ) on the rheology of cement paste, and found that the surface physicochemical properties of nanoparticles (active/inactive, specific surface area, hydrophilicity/hydrophobicity) are the key factors determining the change of rheological parameters. Zhang et al. [18] studied the effect of PNPs on the rheological behavior of cement paste: in the system without water reducer, high anionic PNPs can greatly reduce yield stress and plastic viscosity; while in the system containing polycarboxylate ether (PCE) superplasticizer, PNPs generate dissipative attraction due to non-adsorption, but slightly increase the yield stress. Dhasindrakrishna et al. [19] studied the effect of PVA fibers on the rheological properties of geopolymer foamed concrete, and found that the increase of fiber dosage can increase the yield stress by up to 16 times, and this effect also has a synergistic effect in the nano-modified system.

In summary, the effect of nanomaterials on the fresh rheological properties of foamed concrete is bidirectional: appropriate addition can improve the paste viscosity and yield stress, and enhance foam stability; excessive incorporation may lead to the deterioration of rheological properties and reduce the pumpability and construction workability. Future research should focus on the coupling mechanism of nanomaterial type, dosage, dispersion process and foam system to establish a quantitative relationship model between rheological parameters and foam stability.

3.2. Effect of nanomaterials on mechanical properties of foamed concrete

Foamed concrete has significantly lower mechanical strength than ordinary concrete due to its high porosity, which limits its application in structural components. In recent years, nanomaterials have been gradually introduced into the foamed concrete system by virtue of small size effect, surface effect and high reactivity, in order to improve its mechanical properties without significantly increasing its self-weight. At present, the most widely used nanomaterials are still NS, CNTs and GO. Nanotechnology in concrete plays a role mainly through two ways: microstructural regulation at the nanoscale and introduction of high-activity nanoparticles to promote hydration reaction [3].

NS is one of the earliest nanomaterials used in the modification research of foamed concrete. In the NS modification research of ultra-light foamed concrete system with a density of 350 kg/m^3, when the NS dosage is 5% and 10% of the cement mass, the 28-day compressive strength of the specimen is increased by 20% and 25% respectively [20]. This strengthening effect is mainly due to the high pozzolanic activity of NS: it can undergo secondary hydration reaction with $Ca(OH)_2$ produced by cement hydration to generate more C-S-H gel, thus densifying the pore wall structure [5]. CNTs also show excellent strengthening effect in foamed concrete. As a one-dimensional nanomaterial, the tensile strength of CNTs can reach more than 100 GPa, and the elastic modulus is about 1 TPa. Appropriate addition (usually about 0.05% of cement mass) can increase the compressive strength of foamed concrete by about 30%, and the improvement range of flexural and tensile strength can reach 40%~50% in some studies; however, excessive incorporation easily leads to poor dispersion and agglomeration, which instead reduces the strength [8]. The oxygen-containing functional groups such as hydroxyl, carboxyl and epoxy groups on the GO surface endow it with good dispersibility in cement paste, which can promote early hydration, refine pore size distribution and strengthen ITZ. Its extremely high specific surface area (theoretical value can reach 2630 m^2/g) also provides a large number of nucleation sites for C-S-H gel [9]. In addition, new nano-additives such as zinc peroxide (ZnO_2) nanoparticles have attracted attention due to their high

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reactivity. Studies have shown that such nanoparticles can effectively enhance the mechanical and durability properties of foamed concrete by filling voids and accelerating hydration reactions [21].

The strengthening mechanisms of nanomaterials on the mechanical properties of foamed concrete can be summarized as follows. (1) Filling effect: nanoparticle size is in the range of 1~100 nm, much smaller than the micron scale of cement particles, which can effectively fill nanoscale pores, reduce the total porosity and refine the pore size distribution; at the same time, it acts as a nucleation site for hydration products to accelerate the early hydration process [22]. (2) Pozzolanic reaction: active nanomaterials such as NS react with $Ca(OH)_2$ to generate more C-S-H gel, further densifying the matrix [5]. (3) Nano-bridging effect: one-dimensional/two-dimensional nanomaterials such as CNTs and GO can generate bridging stress at the crack tip, inhibit the propagation of microcracks at the nanoscale, and improve the toughness and crack resistance of the material [8, 23]. (4) Foam structure optimization effect: nanomaterials can obtain a more uniform and fine pore structure by improving foam stability, indirectly improving mechanical properties, and the relevant mechanism will be described in detail in Section 3.3 [11, 14]. In addition, existing studies further point out that the effect of nanoparticles on improving matrix compactness and ITZ can achieve significant enhancement of mechanical properties without affecting fluidity [24]. In summary, nanomaterials such as NS, CNTs and GO effectively make up for the strength loss of foamed concrete caused by high porosity through multiple synergistic effects such as filling, pozzolanic reaction, bridging and pore structure optimization.

3.3. Effect of nanomaterials on bubble stability of foamed concrete

The performance of foamed concrete is highly dependent on the stability of the bubble structure in the paste stage. Before the setting and hardening of fresh paste, foam often undergoes three typical instability behaviors: drainage, Ostwald ripening and coalescence, resulting in pore coarsening, loss of uniformity, and ultimately deterioration of the mechanical and thermal properties of the material [25]. Drainage refers to the downward flow of liquid in the liquid film between bubbles along the Plateau channel under gravity, weakening the thickness and strength of the liquid film. Ripening is caused by the Laplace pressure difference between bubbles of different sizes, and gas molecules migrate from small bubbles to large bubbles, leading to the shrinkage and disappearance of small bubbles. Coalescence is the process of merging adjacent bubbles into larger bubbles after the liquid film between them ruptures [26]. In cement-based foam systems, ripening is usually considered the main instability mechanism, while drainage mainly plays a role in the case of large bubble size, and its stability criterion is closely related to bubble radius and cement paste yield stress [27]. The emergence of nanomaterials provides a new idea for solving the above foam instability problems.

In the past five years, particle bubble stabilization technology, especially the nanoparticle bubble stabilization strategy based on the Pickering effect, has developed rapidly in the field of foamed concrete. Lv et al. [28] systematically reviewed the latest progress of nanomaterial-based Pickering foams in their review, divided bubble-stabilizing nanomaterials into three categories according to spatial dimensions: zero-dimensional (inorganic/organic nanoparticles), one-dimensional (cellulose nanofibers, nanocrystals, etc.) and two-dimensional (graphene oxide nanosheets, etc.), and pointed out that nanomaterials can act on both the gas-liquid interface and the liquid bulk phase, transforming the interface from liquid-like to solid-like or gel-like, thus significantly changing the morphology and rheological properties of foams. Sun et al. [10]. also comprehensively summarized and prospected the formation mechanism, classification method and performance characteristics of nanomaterial-stabilized Pickering foams, providing a theoretical basis for the further development of nano-bubble stabilization technology in foamed concrete.

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In terms of specific material applications, new particle stabilizers are constantly emerging. As a traditional and classic nano-bubble stabilization material, the bubble stabilization effect of NS has been verified in many studies. She et al. [11] compounded NS with hydroxypropyl methyl cellulose (HPMC) and successfully achieved ultra-stabilization of foam, resulting in more uniform and fine pore structure of foamed concrete. The research of Hou et al. [14] shows that when the NS mass fraction reaches 1.5%, the foam stability can be improved by about 6 times, mainly due to the increase of foaming agent solution viscosity and the appropriate regulation of surface tension by NS. Different from the traditional NS bubble stabilization route, Du et al. [29] recently proposed a brand-new C-S-H/PCE nanoparticle foam stabilizer. This material can be efficiently adsorbed at the gas-liquid interface through surface modification of C-S-H nanoparticles by PCE, forming a gel-like interface film, and significantly inhibiting bubble coalescence and ripening. Experimental data show that the water absorption of foamed concrete doped with C-S-H/PCE nanoparticles is reduced by 27%, the thermal insulation performance is improved by 23.1%, and the mechanical strength is increased by 38.6%, showing the technical advantage of "one agent with multiple effects". Meanwhile, facing the demand for solid waste resource utilization and low-cost bubble stabilization, Song et al. [30] innovatively adopted modified ultrafine fly ash particles (AMFA) as solid stabilizers. Studies show that its foam stability indexes (1 h settlement distance and bleeding rate) are comparable to those of traditional NS, and even exceed the bubble stabilization effect of single NS when compounded with NS; the lightweight foamed concrete with a density of 600 kg/m^3 prepared by this high-stability system has a compressive strength of 3.42 MPa and a thermal conductivity of 0.0914 W/(m·K). In addition, para-aramid nanofibers have also been proved to be used as new nanofiber stabilizers, which can delay bubble coalescence by constructing a fiber network structure and effectively improve the long-term stability of foamed concrete [31].

It is worth noting that CO_2 foams stabilized by nanoparticles are becoming an emerging direction in the field of foamed concrete. NS and nano-$CaCO_3$ (NC) have been used to stabilize CO_2 foams to prepare CO_2 foamed concrete. This technology can simultaneously realize the fixed storage of CO_2 and the enhancement of material properties [32]. Studies show that the foam stability is optimal when the NS dosage is 1% and the NC dosage is 1.5%, the strength improvement range can reach 36%, and the average CO_2 absorption increases by 1.8%. NS synchronously promotes hydration and carbonation processes by virtue of its nucleation effect and pozzolanic effect, while NC acts as a nucleation site for calcium carbonate formation, further promoting the carbonation reaction and strengthening the pore wall structure. Both of them effectively reduce the number of connected pores and pore throat size, optimize the pore size distribution and bubble sphericity, thus reducing water absorption and enhancing mechanical properties.

The bubble stabilization mechanisms of nanomaterials can be systematically summarized as the following four aspects. (1) Gas-liquid interface adsorption and membrane strengthening: nanoparticles are spontaneously adsorbed to the gas-liquid interface due to their high surface energy, and form a composite interface film with high mechanical strength and elastic modulus together with surfactant components, realizing the construction of ultra-stable foams similar to the "Pickering" effect [11, 28]. (2) Regulation of paste rheology: the introduction of nanomaterials can increase the viscosity and yield stress of cement paste, slow down the liquid film drainage rate, and reduce the driving force of bubble floating and coalescence [14, 27]. (3) Pozzolanic reaction and pore wall densification: active nanomaterials such as NS react with $Ca(OH)_2$ to generate C-S-H gel, densify the bubble pore wall, and enhance the deformation resistance of bubbles before hardening [11]. (4) Bubble surface charge regulation: the electrostatic adsorption between negatively charged bubbles formed by anionic surfactants and positively charged cement particles can form a protective

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layer around the bubbles. The doping of nanomaterials can further regulate the zeta potential and electrostatic interaction, stabilize bubbles and inhibit ripening and coalescence [33]. Through the synergistic effect of the above multiple mechanisms, nanomaterials can significantly improve the bubble stability of foamed concrete from foam formation to cement hardening, thus obtaining a more uniform and fine pore structure.

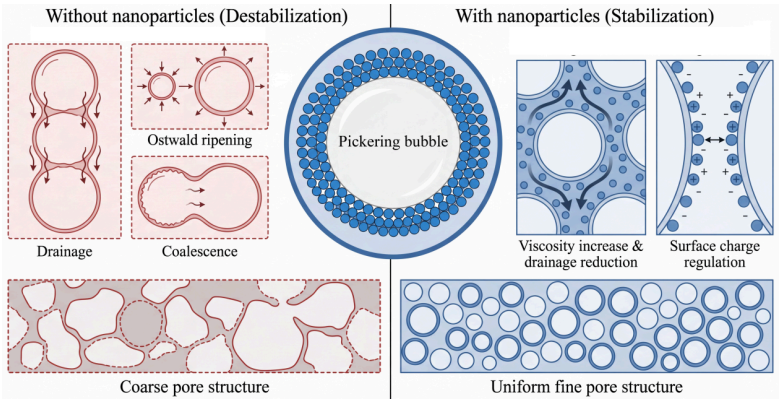


Figure 2. Stabilization mechanism of nanoparticles on bubbles

3.4. Effect of nanomaterials on functionality of foamed concrete

One of the core application advantages of foamed concrete is its excellent thermal insulation performance. The introduction of nanomaterials can further reduce the thermal conductivity on the basis of traditional thermal insulation, and even endow the material with special thermal functions. Embedding nano-aerogel into the matrix of foamed concrete can significantly reduce the thermal conductivity of the material and obtain excellent waterproof performance by virtue of its unique nanoscale pore structure and high hydrophobicity [34]. Recent studies show that doping 4% aerogel can reduce the water content of foamed concrete by 17.4% in the wet saturated state, the dry thermal conductivity by 44.29%, and the wet saturated thermal conductivity by 18.1% [35]. In addition, the synergistic incorporation of hollow glass microspheres (HGM) and aerogel also shows an excellent synergistic optimization effect [35]. Only adding NS can reduce the water content in the wet saturated state by about 5.2%, but it will increase the dry thermal conductivity by about 17.83%, which indicates that the influence mechanisms of different nano/micron materials on the temperature behavior of foamed concrete are essentially different. A latest review also points out that the integration of gas-solid system modification, foam stabilization and nano thermal insulation technologies is the mainstream direction of thermal performance optimization of foamed concrete at present [36].

In addition to the optimization of thermal performance, the introduction of nanomaterials is promoting foamed concrete to develop from a traditional single thermal insulation material to a multifunctional integrated building material, emerging new functions such as photocatalytic self-cleaning, electromagnetic wave absorption and shielding, and self-healing.

Introducing nano-TiO_2 into cement-based materials can endow it with photocatalytic degradation of pollutants and antibacterial functions. TiO_2 can generate reactive oxygen radicals under ultraviolet irradiation, thereby decomposing NO_x and organic pollutants in the air [37]. A number of studies since 2024 have further promoted the technological iteration in this field. The latest work shows that the TiO_2 composite nanofibers modified by graphene can broaden the photoresponse range of TiO_2 to the visible light region, and the pure anatase TiO_2@graphene sample has a degradation efficiency

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of 76.2% for methylene blue under 1.5 W/m² simulated light irradiation [38]. The nano-TiO_2 is loaded on the porous surface of recycled concrete aggregate (RA) through hydrothermal treatment process, and a stable Ti-O-Si chemical bond is formed. The prepared green photocatalytic mortar shows an efficient NO_x removal rate of about 90.75% on average [39]. In addition, some studies have discussed the comprehensive influence of nano-TiO_2 particle size (15\35 nm and 55\75 nm) and dosage (1%~3%) on the fresh state, physical and mechanical properties and photocatalytic performance of cement mortar, providing a systematic reference for performance optimization for specific application scenarios [40]. The above progress shows that the foamed concrete exterior wall system combined with photocatalytic technology is expected to realize the functional integration of building self-cleaning and air purification.

Graphene/carbon nanomaterial modified cement-based composites show great potential in the field of electromagnetic wave absorption and shielding. In the GHz frequency band, the electromagnetic shielding concrete prepared by constructing a multi-scale hierarchical conductive network of nano-carbon black-micron graphite-millimeter steel fiber can achieve a shielding effectiveness of 65~109 dB, while the 28-day compressive strength remains above 45 MPa [41]. The research progress of carbon fiber and carbon nanomaterials (including nano-carbon black, CNTs and graphene) in improving the electromagnetic shielding and wave absorption properties of cement-based materials has been systematically summarized in a Chinese review [42], and new progress has been made in the research on electromagnetic absorption properties of graphene-polystyrene cement-based composites [43]. These studies provide a solid technical foundation for the electromagnetic protection application of foamed concrete in military and civil buildings.

The application of nanomaterials in self-healing cement-based composites has also made significant progress in recent years. On the one hand, bifunctional artificial aggregates containing nanomaterials can realize in-situ expansion compensation and repeated self-healing after concrete cracking, greatly improving structural durability [44]. On the other hand, nano-SiO_2, nano-clay and other materials play a key role in the crack self-healing process through the multiple synergistic mechanisms of nucleation, filling and strengthening [45]. It is worth noting that the cross-integration of nanotechnology and biotechnology is emerging: the bacteria-nano composite system composed of nanomaterials such as NS and nano-$CaCO_3$ synergized with *Bacillus subtilis* spores has a healing efficiency of about 80% for cracks below 0.5 mm, and the durability index is significantly improved compared with traditional self-healing methods [46]. A comprehensive review published in 2025 systematically and in-depth analyzed the application, mechanism, challenges and prospects of nano-engineered self-healing concrete, pointing out that nanomaterials play a crucial mediating role in protecting bacterial spores, improving microbial mineralization activity and promoting biological self-healing efficiency [47]. The above achievements provide a solid technical reserve for the future grafting of self-healing function in the field of foamed concrete.

4. Conclusions and prospects

This paper reviews the effects of nanomaterials on the rheological properties, mechanical properties, bubble stability and multifunctionality of foamed concrete. The main progress is as follows: in terms of mechanical properties, the pozzolanic reaction and filling effect of nano-SiO_2 can densify the pore wall, carbon nanotubes and graphene oxide inhibit the propagation of microcracks through bridging effect, and the three synergistically make up for the insufficient strength of foamed concrete caused by high porosity. In terms of bubble stability, nanoparticles improve foam stability through various mechanisms such as interfacial adsorption, paste rheological control, pozzolanic reaction and surface charge regulation. Particle bubble stabilization technology based on Pickering effect has

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achieved remarkable results, and the development of new stabilizers such as C-S-H/PCE nanoparticles and modified fly ash further enriches the bubble stabilization approaches. In terms of functionality, nano-aerogel can reduce thermal conductivity and improve water resistance, nano-TiO_2 endows materials with photocatalytic self-cleaning ability, carbon-based materials realize electromagnetic shielding function, and nano-bacteria composite system shows crack self-healing potential. Foamed concrete is developing from a single thermal insulation material to multifunctional.

Current research still faces the following problems: the dispersion technology of nanomaterials in cement matrix is not mature, the cost of some high-performance nanomaterials is high, the collaborative optimization mechanism between mechanical, thermal and functional properties is not clarified, the evaluation data of long-term durability and environmental risk are insufficient, and there is a lack of unified testing and evaluation standards. Future research should focus on developing efficient dispersion methods suitable for cement systems and low-cost nano-modified materials, establishing a quantitative relationship between composition-structure-performance through multi-scale characterization, promoting multifunctional collaborative design, carrying out long-term performance and environmental impact assessment, and establishing relevant standards and specifications to promote the engineering transformation of nano-modified foamed concrete.

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