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Review Article

Foam Concrete: A State-of-the-Art and State-of-the-Practice Review

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Foam concrete (FC) has the potential of being an alternative to ordinary concrete, as it reduces dead loads on the structure and foundation, contributes to energy conservation, and lowers the cost of production and labor cost during the construction and transportation. The paper reports a state-of-the-art review of foam concrete in terms of its components, manufacturing and material properties like drying shrinkage, compressive strength, stability and pore structure, etc. In view of the significance of the FC in engineering construction, it also includes a state-of-the-practice review of foam concrete in tunnel and underground engineering. Some shortcomings and technical limitations as well as emerging direction for performance enhancement of FC are also discussed. Current review concludes that the long-term performance and enhancement-associated properties need to be deeply investigated. This study can help alleviate consumer concerns and further encourage the wider application of FC in civil engineering.

1. Introduction

FC is a type of cement mortar containing cement, water, and stable and homogeneous foam introduced using a suitable foaming agent [1–3], which can be regarded as self-compacting materials [4]. Other academic terms describing this material are lightweight cellular concrete [5], low-density foam concrete, or cellular lightweight concrete, etc. [6–8]. In practice, it provides satisfactory solutions to address various challenges and problems faced in construction activities. Fewer chemicals containing in this material well meets the sustainable and environmental demands, and sometimes, it can be partially or even entirely substituted for normal concrete [9, 10]. The textural surface and microstructural cells make it widely used in the fields of the thermal insulation [11, 12], sound absorbance [13, 14], and fire resistance [15, 16]. A great number of environmentally friendly buildings using FC as nonstructural members have been built in recent years [17, 18]. It is also used for bridge abutment filling to eliminate differential settlement [19]. In addition, the applications for prefabricated components production [20], building foundation [21–23], and airport buffer system are also reported [24]. Foam concrete has been commonly used in construction applications in different countries such as Germany, USA, Brazil, UK, and Canada [25].

This material has renewed interests in terms of underground engineering. This is the requirement of underground structure to control the overlying dead load [26–34], whereas the controllable density and low self-weight [35, 36] could be effectively used for reducing the dead load. Other properties, such as seismic resistance, ideal coordinated deformation capacity, and easy pumping, also contribute to enhance the popularity of this material [37, 38]. Nowadays, the FC has been quickly promoted as construction materials for tunnels and underground works. Its excellent selfflowing capacity can be used to fill voids, sink holes, disused sewage pipes, abandoned subways, and so on. The low and controlled self-weight makes it capable for load reduction or liner elements in tunnel and metro systems [39–41].

Though there are limited studies regarding the practical applications of FC in civil engineering, its properties have been deeply studied. For example, Tan et al. [42] performed an investigation on compression deformation properties of FC used as liner element for the purpose of further explaining stress and strain response. The experimental results indicated that the compressive strength of FC increases with density and confining pressure, whereas the modulus of elasticity has a positive correlation only with densities regardless of confining pressure. And no notable correlation was observed between peak strain and density, but peak strain increases with confining pressure. Tikalsky et al. [43] studied the freeze-thaw durability of cellular concrete and proposed an improved freeze-thaw test method. They reported that depth of absorption was considered as a critical predictor in developing freeze-thaw-resistant concrete, which will contribute to promote effectiveness in terms of using FC as insulation material for tunnels in cold regions. Sun et al. [44] explored the influence of different foaming agents on compressive strength, drying shrinkage, and workability of FC, which will be helpful to determine specification and implementation details. Moreover, Amran et al. [37] reviewed the composition, preparation process, and properties of FC, while the focus of a review organized by Ramamurthy et al. [38] is to classify literatures on foaming materials, foaming agents, cement, fillers, mix proportion, production methods, fresh and hardened properties of FC, etc. Significant progress of FC application has been made over the past few decades. In Canada, cement-based FC has been widely used for tunnel grouting [45]. Zhao et al. [46] developed a foam cement-based material as a sacrificial tunnel lining structural cladding used under the situation of blasting load action. This FC-based sacrificial cladding with the optimized thickness effectively alleviates the dynamic responses induced by blasting loads in tunnel. Choi and Ma [47] employed lightweight FC to facilitate tunnel drainage, whereas it was successfully implemented in a two-lane highway tunnel in South Korea. Successful application was achieved due to the effective formation and distribution of open-cell foams, with excellent permeability.

With the booming development of FC and manufacturing technology, FC application in tunnels and underground works has revealed prominent prospects. This review briefly describes the history and development of FC, and some forward-looking perspectives are also discussed. The FC engineering properties and benefits to engineering construction are elaborated. The objective of this review is to highlight engineering properties, material properties, and the practical applications in tunnel and underground engineering.

2. Foam Concrete

2.1. History and Recent Development. There is a confusion existed between FC and similar materials in early literatures, i.e., aerated concrete and air-entrained concrete [48]. However, one definition (i.e., FC is defined as a cementing material with the minimum of 20% foams by volume in the mixed plastic mortar) introduced by Van Dijk [49] clearly distinguish the FC from aerated concrete [50, 51] and air-entrained concrete [52]. The closed air-voids system in FC notably reduces its density and weight and at the same time produces efficient insulation and fire resistance capacity [26, 53].

The first Portland cement-based FC was patented by Axel Eriksson in 1923, and then, small-scale commercial production activities were launched [54]. Valora carried out the first comprehensive investigation in the 1950s [55]. Rudnai [56] and Short and Kinniburgh [57] systematically reported the composition, properties, and applications of the FC later. FC was initially envisaged as a void filling, stabilization, and insulation material [58]. The booming development of this new constituent material in buildings and constructions was enhanced in the late 1970s [59]. A government-oriented assessment on FC could be seen as a milestone event to further widening FC applications.

Over the past 30 years, FC are widely used for the bulk filling [38], ditch repair, retaining wall [60], bridge abutment backfill [17], slab structure of concrete floor [18], and housing insulation [37], etc. (Figure 1). Currently, people are increasingly interested in using it as a nonstructure or semistructure member for underground engineering, such as grouting works for tunnels, damage treatment, and liner structures.

2.2. Material Components and Preparation. The basic components of FC consist of (1) water, (2) binder, (3) foaming agent, (4) filler, (5) additive, and (6) fiber. The state-of-the-art research and findings on these components to date are described as follows:

Water: The water requirement for constituent material depends on composition, consistency and stability of the mortar body [38]. The lower water content leads to a hard mixture, which easily resulting in bubble bursting [61]. The higher water content causes mixture too thin to accommodate bubbles, thereby causing bubbles separating from the mixture [1]. The American Concrete Institute (ACI) recommends that mixed water should be fresh, clean, and drinkable [62]. Sometimes, the mixed water can be replaced by equivalent-performance water received from municipal sectors in case the strength FC could reach 90% within specified curing time [38].

Binder: Cement is the most commonly used binder. The ordinary Portland cement, rapid hardening Portland cement, calcium sulphoaluminate cement, and high-alumina can be used in ranges between 25% and 100% of the binder content [59, 63].

Foaming agent: The foaming agent determines FC density by controlling generation rate of the bubbles in cement paste. The resin-based was one of the earliest used foaming agents in FC. So far, synthetic, protein-

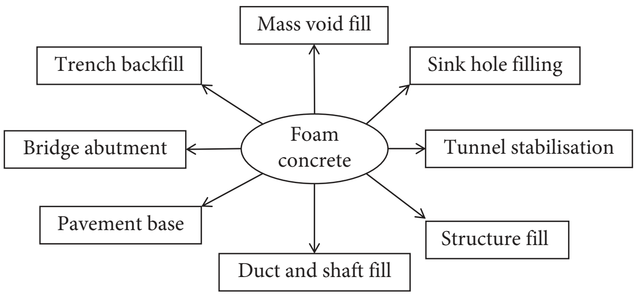


Figure 1: Different applications of FC.

based, composite and synthetic surfactants have been derived and developed, while the most frequently used are synthetic and protein-based ones [64].

Filler: Various fillers such as silica fume, fly ash, limestone powder, granulated blast furnace slag, and fly-ash ceramicite [61] have been widely adopted for the purpose to enrich FC mechanical performances [65–67]. Addition of these fillers is helpful to improve mix proportion design, long-term strength, and reduce costs. In addition, some fine aggregates such as fine sand [68], recycled glass powder [69], and surface modified chip [70] are commonly used for production of high-density FC.

Additive: Commonly used additive includes the water reducer, water-proofing additive, retarder, coagulation accelerator, etc. Plasticizers are always considered to enhance compatibility [43]. In fact, they are defined as water reducers to improve performance of fresh concrete by reducing fluidity and plasticity, and there is no notable impact on concrete segregation was observed [71, 72].

Fiber: A variety of fibers are added into FC so as to improve strength and reduce shrinkage. They are mainly polypropylene [73, 74], glass and polypropylene [75], red ramie [76, 77], palm oil, steel [78], coconut [79], waste paper cellulose [80], carbon, and polypropylene [81], which usually introduced in ranges between 0.2% and 1.5% of the mixture volume.

FC is commonly prepared by prefoaming method or mix-foaming method [37]. The majority of common mixers such as the inclined drum, pan mixer used for concrete, or mortar is applicable to FC production. The mixer type, mix proportion, and mixing order used for FC depend on adoption of the above-mentioned two methods [38]. The major procedures using these two methods are presented as below:

Prefoaming Method. (1) The foam and base mixture are prepared independently. (2) Totally mix the foam and base mixture [82].

Mix-Foaming Method. (1) Surfactants or foaming agent are mixed with base mixture together (especially the cement paste). (2) The foam produces cellular structures in FC.

There are two ways, i.e., dry or wet process, used for bubble generation. The dry process produces more stable bubbles with sizes less than 1 mm compared to the wet process, for which the sizes of the generated bubbles are between 2 mm and 5 mm. The stable foam helps to resists mortar pressure until cement solidifies, which is advantageous to generate reliable pore structure in FC [83].

Though the mixing process and FC quality in these two methods can be controlled, the preforming method is considered superior to mix-forming method due to the following [84].

(1) Lower requirements for foaming agents [55]

(2) The foaming agent content is closely related to air content in mixture

2.3. Material Properties. Currently, weakness and poor durability on FC still exist. The discussion on the material properties in this section is mainly based on practical applications, where there are potential problems such as (1) underground water, (2) insufficient structure strength, (3) structure crack/failure, (4) stabilization issue, and (5) corrosion. The material properties like drying shrinkage, compressive strength, and durability, are discussed through literature review.

2.3.1. Drying Shrinkage. Lack of coarse aggregates leads to 4–10 times higher shrinkage of the FC than that observed in ordinary concrete [15, 37]. There are many factors affecting the drying shrinkage, such as density, foaming agent, filler, additive, and moisture contents. Table 1 presents different drying shrinkage values observed in some cement-based materials.

In general, drying shrinkage decreases with the density reduction [37]. The shrinkage differences induced by foaming agents are bound up with pore structure of FC, and the lower pore connectivity helps to reduce the drying shrinkage [44]. Jones et al. [86] observed the decrease of drying shrinkage when fine sand was used as fillers instead of fly ash, because the fine sand provides a superior capacity in resisting shrinkage deformation. Many findings demonstrate that fine aggregate such as light ceramsite [87], expanded perlite, vitrified microsphere [88], and magnesium expansive agent [89] together with reduction of foam volume [90] can reduce drying shrinkage. Meanwhile, restrictive effects from increase of water and aggregate also provide support for drying shrinkage reduction [91].

It is reported that autoclaving technique reduces 12–50% drying shrinkage and brings a strength enhancement; therefore, autoclaving is an ideal option for maintaining FC products within an acceptable strength and shrinkage level [15]. To reduce drying shrinkage, some aspects like water content control, selection of binder and foaming agent as well as mixture modifying with fine aggregate are worthy of further studies. The use of fibers can significantly enhance resistance capacity on drying shrinkage due to (1) tensile strength improvement of cement base mixture, (2) prevention of further cracks development in cement base mixture, and (3) capacity improvement of resisting deformation. Table 2 summarizes and reviews different results and findings on the drying shrinkage.

Table 1: The drying shrinkage values observed in typical cement-based materials [85].

Material	Cement paste	Cement mortar	Cement concrete	FC
Drying shrinkage (%)	0.15–0.3	0.08–0.2	0.06–0.09	0.15–0.35

Table 2: Review of filler, foaming agent, and additive used in FC, and the resulting density ranges and drying shrinkage.

Filler	Foaming agent	w/c ratio	Additive	Density (kg/m^3)	Drying shrinkage (%)	Reference
Blast-furnace slag + limestone fine	Fatty alcohol-based liquid	0.29	Magnesium expansive agent + calcium sulfoaluminate	1611–1638	0.05–0.32 28 d	[89]
Polymer fiber	Foamin C$^{@}$	0.3	Viscosity enhancing agent	380–830	0.1–0.49	[92]
N/A	Animal based + synthetic + plant based surfactants	0.5	N/A	600	0.25–0.3 90 d	[44]
Crushed sand + FA	Hydrogen peroxide	0.3	Na_2SiO_3 + NaOH	1889–2106	0.09–0.1 180 d	[93]
FA + natural sand	Protein foaming agent	0.71–2.22	N/A	1000–1400	0.09–0.2 365 d	[94]
N/A	Synthetic polymeric latex	0.45–0.6	N/A	260–800	0.18–0.31	[95]
N/A	Synthetic based	0.52–0.75	N/A	300–800	0.26–0.35 90 d	[96]
Sand	Hydrolyzed protein	0.5	N/A	900–1100	0.7–0.72 28 d	[97]
Quartz sand	PB-2000	N/A	Microreinforcing additive	N/A	0.15–0.3	[98]
FA	Organic based	0.3–0.5	Na_2SO_4 + Triethanolamine	400–800	0.09–0.18 28 d	[99]

N/A, not available; FA, fly ash.

Some adverse factors such as poor early curing, insufficient water conservation measures, or harsh production conditions may cause water evaporation, thereby leading to shrinkage or even crack in FC. Some technical measures improving these situations are illustrated as following:

(1) Suitable cement dosage.

(2) Lower water-cement ratio.

(3) Strengthen water conservation in early stage.

(4) Use waterproofing agent.

(5) Use crack prevention net.

2.3.2. Compressive Strength. Though FC has been deeply studied, some shortcomings such as low strength still restrict its wider applications [100]. The strength of FC is determined by different cementitious materials, cement dosage, mix proportion, water-cement ratio, foam volume, foaming agent, curing method, additive, etc. [101]. Table 3 illustrates some studies on different factors affecting FC compressive strength.

To a certain extent, the density controls the strength. Hence, it is always to seek a balance between strength and density, for the purpose to maximize strength while reducing density as much as possible. Sometimes, this can be achieved through optimizing cementitious materials and selecting high-quality foaming agents and ultralight aggregates. Nambiar et al. [1, 61] indicated that the filler types determine the water-solid ratios when FC density is constant, and the reduction of sand particle size will help to improve strength. The foam volume exerts a notable impact on the flow behavior of FC, and a reduction in particle size of filler shows a positive effect on strength improvement of FC. Park et al. [111] added carbon fiber into base mixture so as to produce carbon-fiber-reinforced FC, and they reported that the strength and fracture toughness were obviously improved due to carbon fiber reinforcement effect. The results confirmed that reasonable water-cement ratios exhibit a notable impact on enhancing the strength. The higher water-cement ratio ensures excellent slurry fluidity thereby introducing foam into cement paste with an even distribution, so as to achieve strength growth. On the contrary, the decrease of water cement ratio results in poor fluidity, thus reducing the strength. The dominant factor affecting strength is cement quality added into mortar slurry, whereas the high strength cement is considered as an effective way for strength enhancement. However, it should be added appropriately considering the increase of subsequent cost.

The investigation indicated that FC strength decreases with the voids increase [112–114]. The impact of foaming agent on strength is mainly manifested in aspects of the bubble size, distribution uniformities of bubbles, foam stability, and foaming capacity. Ideally, foaming agents should be characterized by strong foaming capacity, poor water-carrying capacity per unit, and little adverse impacts on FC [115–118]. Attempts and investigations can be considered regarding selection of the high-performance foaming agent so as to prepare the small and uniform bubbles. The experimental results showed that the water-cement ratio and air-ash ratio have crucial impacts on FC

Table 3: Overview on research on factors affecting compressive strength of FC.

Composites	Factors investigated	28 d CS	Main findings and conclusions	Reference
OPC	(i) Curing condition (ii) Fiber content (iii) Dry density	1.56–13.38	(1) Compressive strength increases with dry density increase in nearly linear, while bending strength increases more obviously. (2) The flexural strength was significantly increased when fiber content increased to a certain extent, but the compressive strength was not significantly affected.	[92]
Cement, sand	(i) Coconut fiber content	9.6–14.6	(1) The volume increase of coconut fiber particle aggregate in FC can significantly enhance compressive strength with a maximum value of 15%.	[102]
OPC	(i) Water-cement ratio	3–5.1	(1) The FC compressive strength varies in an inverted V-shape with the increase of water cement ratio.	[103]
OPC	(i) Bentonite slurry content	3–4.7	(1) The compressive strength decreases with mixing content increase of bentonite slurry.	[104]
OPC, GBFS, FA	(i) Foam stabilizer	1.7–2.3	(1) XG stabilizer performs positively on thermal conductivity and compressive strength of FC. (2) The compressive strength with mechanical and chemical foaming increased by 34% and 20%, respectively.	[105]
OPC	(i) Foaming agents (ii) Dry densities (iii) Cement type	0.20–11.74	(1) The compressive strength increases more obviously when protein based foaming agent is used in mix design as its positive effect on pores. (2) The maximum strength value was recorded in cellophane curing while the minimum one was found in air curing.	[7]
OPC	(i) Aggregate substitution	3–48	(1) Slag partially substituted for fly ash improves FC strength at room temperature, but leads to a drying shrinkage and strength loss at high temperature.	[19]
Cement, natural sand	(i) Additive types	6–47	(1) The reinforcement of pore structure and microstructure improvement of cement paste are helpful to improve FC strength. (2) The combination of additives reduces size and connectivity of pores and prevents them from merging as well as produces narrower pores distribution, and achieves higher strength.	[106]
OPC	(i) Different sand grading	5.6–7.0	(1) The samples prepared with 0.60 mm sand have the highest compressive strength compared to those prepared with coarse sand grade. (2) The whole water curing provides a better development environment for strength increase compared to the air curing.	[107]
OPC	(i) Different pumice types	0.5–3.5	(1) The pumice-based FC has the highest compressive strength. (2) The density-based empirical model for compressive strength prediction was proposed.	[5]
OPC, fine sand,	(i) Different filler types	4–23	(1) Adding superfine GGBS as a partial substitute for cement can increase strength slightly without significantly changing mix and workability. (2) The strength with small pore diameter and uniform pore size is higher than other samples.	[108]
OPC	(i) Recycled waste as filler	1.53–10.26	(1) Recycled glass-filled FC has higher compressive strength compared to that filled with plastic. (2) The addition of superplasticizer reduces the amount of macropore and greatly improves the strength.	[109]
OPC, sand	(i) Recycled waste as filler	5.2–6.8	(1) Compared with FC produced with 100% addition of river sand, using refined mineral powder as filler can improve compressive strength and strength performance index.	[110]

OPC, ordinary Portland cement; FA, fly ash; CS, compressive strength (unit: MPa); GBFS, granulated blast furnace slag.

strength [119, 120]; it also reported that addition of fibers is helpful to increase strength [73, 74, 121]. The prediction models on compressive strength were also investigated by some researchers. These findings are mainly based on the artificial neural network [122–124], extreme learning machine [125], and regression analysis based empirical models [126]. Table 4 summarizes the prediction models for compressive strength of FC to date.

2.3.3. Durability. The underground members are usually faced with various adverse conditions such as temperature change, freeze-thaw cycles, and acid-base corrosion. These factors may lead to a poor durability of the FC-based structures and members, resulting in structural damages, which seriously affects project safety.

(1) Permeability. Water absorption of FC is attributed to the capillary pore infiltration and connected pore infiltration. Cox and Van Dijk [134] reported that the water absorption of FC was higher than that observed in other concrete types due to the least 20% foam embedded in plastic mortar. This capacity is generally twice than that of the normal concrete with the same water-binder ratio [63]. An investigation conducted by Nyame [135] found that permeability of concrete mortar

Table 4: Prediction models for compressive strength of FC.

No.	Components	Equations	Annotations	Reference
1	OPC and limestone powder	$f_c = 0.0029 \times \exp(0.0104\gamma)$	γ = dry density (kg/m^3)	[5]
2	OPC, fine sand and FA	$f_c = A(\ln t)^B (S_a(m_c + m_m) + m_s/\gamma)^C$	A, B and C = parameter reflecting compressive strength, hydration rate and porosity of mix, t = curing time, S_a = empirical constant, m_c, m_m and m_s = cement, admixture, fine aggregate dosages per cubic meter	[127]
3	Cement, FA and slag	$f_c = A \times \exp(a \times p_1) + B \times \exp(b \times p_2)$	a, b = empirical constants, A, B = fitting constants, p_1, p_2 = porosity.	[128]
4	Cement, FA and slag	$f_c = C \times (1 - p_1)^c + D \times (1 - p_2)^d$	c, d = empirical constants, C, D = fitting constants	[128]
5	OPC and FA	$f_c = 0.0243 \times \exp(0.0083\gamma)$	γ = dry density (kg/m^3)	[12]
6	Cement and sand	$f_c = 0.34\exp[0.0022c \times (1 + (w/\text{cm}) + (s/c))]$	c = cement content, w = cm = water to cementitious material ratio, s/c = sand-to-cement ratio	[126]
7	Cement, sand and FA	$f_c = f[d_c(1 + 0.2\rho_c + s_v)/(1 + k_s)(1 + s_w)\rho_c\gamma_w]^b$	b = empirical constant, s_w = filler-cement ratio by weight, s_v = filler-cement ratio by volume, f = theoretical strength of a paste with zero porosity, k_s = water-solids ratio by weight, γ_w = unit weight of water, d_c = fresh density, ρ_c = specific gravity of cement	[114]
8	Cement, sand and FA	$f_c = K[2.06 \times \alpha \times V_c/1 - V_{fl} - V_c(1 - \alpha)]^n$	V_c = volume of cement, V_{fl} = fillers volume per cubic meter of concrete, α = hydration degree, K = gel intrinsic strength, n = empirical constant	[114]
9	Cement and FA	$f_c = f(-0.324 + 1.325\alpha_d)^2$	α_d = dry density ratio	[129]
10	Cement and FA	$f_c = 39.6(\ln(t))^{1.174}(1 - p)^{3.6}$	p = porosity	[129]
11	Cement and ash	$f_c = l(a/c)^2 + m(a/c) + n$	a/c = ash/cement ratio by weigth, l, m and n = constants	[130]
12	Cement and FA	$f_c = 188[d_c(1 + 0.2\rho_c)/(1 + k_s)\rho_c\gamma_w]^{3.1}$	d_c = fresh density, ρ_c = specific gravity of cement, γ_w = unit weight of water	[131]
13	Cement and ash	$f_c = 1.172 f\alpha_b^{3.7}$	α_b = binder ratio by volume, f = cement paste compressive strength	[63]
14	Cement and sand	$f_c = k(c/c + w + a)^n$	c, w, and a = absolute volumetric Proportions of cement, water, and air, k and n = constants	[119]
15	Cement	$f_c = K_S\ln(p_{os}/p)$	K_s = empirical constant, p_{os} = porosity at zero-strength	[132]
16	Cement	$f_c = 245[d_c(1 + 0.2\rho_c)/(1 + K_s)\rho_c\gamma_w]^{2.7}$	ρ_c = specific gravity of cement, γ_w = unit weight of water, K_s = empirical constant	[133]

decreases with porosity decrease after the addition of the aggregate. An increase of the aggregate volume in mixture leads to the increased permeability. Meanwhile, the increase of ash/cement quantity in base mixture proportionally increases the water vapor permeability, especially at low densities [114]. Kearsley et al. [131] studied the influence of different fly ash types on the porosity and permeability. The results showed that dry density directly affects the porosity, but slight impacts of fly ash on porosity were observed. In addition, an empirical model for permeability prediction was proposed:

$$k_d = \frac{Gd}{A_c t \Delta p}, \quad (1)$$

where k_d = vapor flow time rate through unit area, G = weight loss thorough t time in hours, A_c = cross sectional-area perpendicular to flow (m^2), d = thickness of specimen in m, t = time in hour, and Δp = distance between dry and moist sides of the specimen.

Different methods were employed by Hilal et al. [136] to investigate effects of pore structure, porosity, and critical pore size on permeability and water absorption of FC. The results showed that the critical pore diameter and the pore diameter size (>200 nm) decrease with density increase, which is closely related to the permeability. Therefore, the manufacture ability to ensure air being contained in stable, small, and uniform bubbles should be highlighted, which is helpful to reduce the permeability of cement paste due to their integrity and isolation effects.

The adsorption of FC mainly depends on filler types, pore structure, and infiltration mechanism. It was reported that filling effect from mineral aggregates affects the pore structure and permeability of cement paste [137]. Jones and McCarthy [138] compared adsorption differences between sand-based and fly ash-based FC. The results indicated that the fly ash-based mix was endowed with higher water absorption than that mixed with sand. The FC adsorption was generally lower than the corresponding basic mixture and decreases with foam volume increase [139]. An investigation conducted by Awang and Ahmad [78] demonstrated that the water absorption dramatically increases owing to the use of steel and polypropylene fibers in the basic mixture. Each kind of fiber has a different surface morphology that plays an important role in the water absorption rate of lightweight FC. Another study suggested that using pozzolanic admixture and turbulent mixing technique can produce water-resistant and durable FC [140].

(2) Frost Resistance. Freeze-thaw cycle is one factor that responsible for deterioration and failure in concrete [141, 142]. An investigation carried out by Tsivilis et al. [143] revealed that addition of limestone powder reduced frost resistance of FC and limestone cement concretes indicate lower resistance to freezing and thawing compared to the pure cement concrete. Tikalsky et al. [43] performed freeze-thaw cycling tests on FC with different mix proportions based on an improved method, and it is found that the compressive strength, initial penetration depth, and water absorption have significant effects on the frost resistance, but little effects of density and permeability on frost resistance are observed.

(3) Carbonization. Carbonization increases the risks of cracking and durability loss of FC [140]. Jones and McCarthy [59, 138] also reported that a higher incidence of carbonization was observed in low-density concrete. Compared with fine sand replaced mixture, replacing fly ash with cement in mixture notably improved carbonization resistance capacity [86]. In addition, the foam content increases with decrease of foam density so as to reduce carbonization in FC.

(4) Corrosion. The resistance capacity of FC to erosive environment depends on its cellular structure. However, this structure does not necessarily reduce resistance capacity for water penetration, whereas voids produced cushioning effect to prevent rapid penetration [139]. Sulfate is one of the corrosive agents that affect the service life of FC while the damage risk from alkali-silicon reaction on recycled aggregate is not significant [144]. Sulfate erosion is identified as a complex process and can be influenced by various factors such as cement type, water-cement ratio, exposure time, mineral admixture, permeability, etc. [145–147]. Ranjani and Ramamurthy [148] carried out 12 months of continued assessment on FC performance with variable densities of 1000 to 1500 kg/m^3 by immersing FC examples in sodium sulfate solutions and magnesium sulfate solutions, respectively. The results showed that expansion rate of FC in sodium sulfate environment was 28% higher than that in magnesium sulfate environment, leading to a 1% mass loss of specimens in magnesium sulfate environment. In addition, the corrosion resistance capacity of studied samples increases with the decrease of FC density [149].

2.3.4. Thermal Conductivity. Outstanding thermal insulation properties of FC make it popular in the building insulation. It is widely reported in relevant studies that thermal conductivity is an important parameter influencing thermal insulation performance. FC has excellent thermal insulation properties due to its porous structure. The thermal conductivity values are 5–30% of those measured on normal concrete and range from 0.1 to 0.7 W/mK for dry density values of 600–1600 kg/m^3, reducing with decreasing densities [150]. The thermal conductivity of FC is controlled by the filler, density, fiber, mix ratio, temperature, and pore structure.

(1) Influence of Filler. Different aggregates and mineral admixtures have a significant effect on thermal conductivity. It was observed that the addition of the lightweight aggregate in FC reduces the thermal conductivity [151]. It is specified that thermal conductivity value for lightweight aggregate FC with a dry density of 1000 kg/m^3 is 1/6 of that measured on typical cement mortar [152]. Artificially introducing pores into the mortar matrix combining with the use of lightweight aggregate with low particle density has been identified to be helpful for reducing thermal conductivity [91]. FC with a thermal conductivity value of 0.06–0.16 W/mK could be produced by moderately filling polystyrene particles into porous mortar [153]. Giannakou and Jones [154] stated that the excellent properties of fly ash, such as low density and hollow particles are advantageous to increase the heat flow paths so as to reduce the thermal conductivity. In a study by Jones and McCarthy [88] reported that typical thermal conductivity values of FC with dry density of 1000–1200 kg/m^3 range between 0.23 and 0.42 W/mK. And 30% replacement of cement by PFA (pulverized fuel ash) has also been confirmed to lead to a 12–38% reduction on thermal conductivity. Studies done by Xie et al. [104] found that use of bentonite slurry improves the thermal insulation performance of FC and observed that with densities of 300 and 600 kg/m^3, the samples with 10% bentonite slurry underwent the largest reduction in thermal conductivity.

(2) Influence of Density. For FC, it was found that the thermal conductivity reacts proportionally with a density. Weigler and Karl [91] observed a 0.04 W/mK drop in total thermal insulation was observed with each 100 kg/m3 reduction of the density. The thermal insulation performance decreases as the density volume increases [155, 156]. In terms of the application of FC in wall brick masonry, an increase up to 23% on thermal insulation was obtained comparing to the normal concrete when the inner leaf of the wall constructed with the FC at a density of 800 kg/m^3 [111].

(3) Influence of Fiber. Nagy et al. [78] studied the thermal conductivity of several fibers consisting of AR-glass, polypropylene, steel, kenaf, and oil palm fibers. The results showed that the thermal conductivity on samples with steel fiber inclusion is higher than those observed in FC with other fibers inclusion, while polypropylene fiber presented the lowest thermal conductivity. This is explained to be expected because steel fiber itself is a good heat transfer conductor. Also, the higher the fiber inclusion, the higher the thermal conductivity. In another study, Nagy et al. [157] investigated the thermal properties of steel fiber reinforced concrete and observed that the addition of steel fiber does not necessarily increase the thermal conductivity. This is because the addition of fiber leads to the increase of porosity,

which reduces the density and thermal conductivity. The durability properties of FC consisting of five different synthetic and natural fibers like polypropylene, AR-glass, kenaf, steel, and oil palm fibers were studied by Awang et al. [158]. They confirmed that the maximum reduction in shrinkage and the thermal conductivity was obtained from using polypropylene fibers.

(4) Influence of Mix Ratio. The insulation capacities of FC are proven to be sensitive to the change of mortar-foam ratios [49]. This difference is more obvious in low-density samples ranging between 200 and 300 kg/m^3 [159]. The denser cement paste with a lower water cement ratio is easier to form pores with lager size than that with a higher water cement ratio. Thus, the convective heat transfer in the larger pores under the temperature difference increases the thermal conductivity of the FC with lower water cement ratio [159].

(5) Influence of Temperature. It is reported that the thermal insulation is improved with the decrease of temperature. Richard et al. [160] studied the thermal insulation performance of porous concrete applied in a low temperature environment, and satisfactory results were observed. At the same time, Richard et al. [161] reviewed the thermal and mechanical properties of FC in the density range of 640–1440 kg/m^3 with the ambient temperature ranging between 22 and −196°C. The results indicated that the thermal conductivity value of foam concrete significantly reduced by 26% when the temperature falls from 22 to −196°C.

(6) Influence of Pore Structure. According to Kumar et al. [162], the thermal conductivity was about 50% lower than that of normal concrete with a thermal conductivity of 1.43 W/mK as a result of the uniform pore size in cellular lightweight concretes (CLCs). FCs with larger size and the wider distribution of bubbles were found to have lower thermal conductivity at low densities [104]. Also, it was shown that higher the porosity, the lower the thermal conductivity. However, the increase of the joint strength of pore paths was found to occasionally increase the thermal conductivity. The location and relative orientation of the pores have a great influence on the thermal conductivity. More thermal resistance was observed when the pores are arranged at right angles to the heat flow, leading to more heat passing through the pores. On the contrary, if a layer of pores is parallel to the direction of heat flow, a smaller thermal resistance will be produced [163].

2.3.5. Pore Structure. A critical task in FC production is to control the nature, size, and distribution of pores, because the pore characteristic is the key factor to determine the density and strength of FC. Pores can be generated by (i) mixing a gas releasing agent such as H_2O_2 or zinc powder in the pasteur cement mortar, or (ii) introducing a large volume of bubbles in mortar. Often different foaming methods, composition of mixture, and curing process will produce individual bubbles with different sizes and distributions, which further affects performance of the FC.

The pore characteristic is an important factor that controls the compressive strength, thermal conductivity, and permeability of the FC. These pores are composed of the interlayer pores/spaces, gel pores, capillary pores, and air void, with pore sizes varying from nanoscale scale to millimeter scale [128]. Some parameters such as volume, size, size distribution, shape, and spacing of pores can be used to characterize these pores [38]. The gel and capillary pores are mainly responsible for the microstructure features [53]. The use of additives and the variation of water cement ratio will affect the pore characteristics. For a given density, the addition of additive reduces the pore size and connectivity so as to obtain the higher strength. The introduction of mineral admixture such as slag or fly ash in FC results in a reduction on the pore size distribution and total porosity [164]. Batool et al. [165] studied the distribution features of pore size in cement-based FC. The results showed that narrower the pore distribution, the greater the conductivity and the smaller the density. The addition of superplasticizer in combination of other additives in foam concrete can further benefit improvement of the pore structure [106].

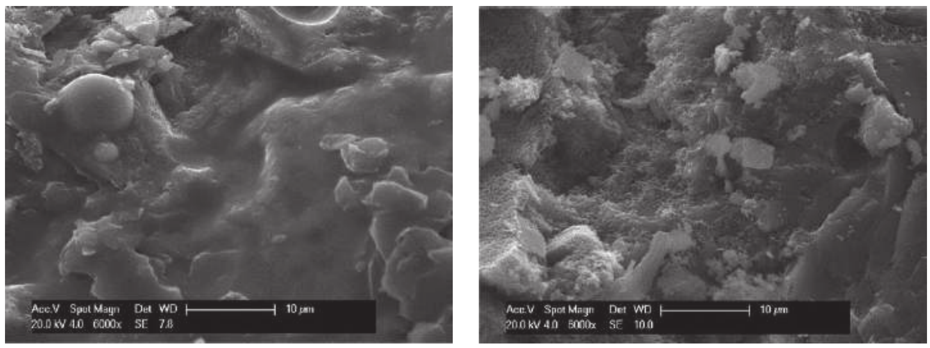
Researchers found that the pores may be influenced by water cement ratio owing to the changes in the rheological properties and the ability to resist collapse from the foams. It is observed that the pores were small, irregular-shaped, and highly connected at water cement ratios below 0.8. These pores were determined to be rounded, expansive, and with wider pore size distribution for water cement ratios over 0.8, because the ability to limit the growth of air bubbles decreased at high water cement ratios [166]. It is reported that reduction of water cement ratio or the addition of fillers often brings difficulties in generating an arranged pore area [53]. Lower water content helps FC to capture the smaller pore size as well as the increased mass density and compressive strength [53]. Pore distribution is one of the important microscopic parameters affecting the strength of foam concrete. In general, foam concrete with narrower bubble distribution will have the higher strength [118].

A review by Zhang et al. [26] summarizes the effects of foaming method on pore properties like size, volume, and shape, as shown in Table 5. It is observed that pore sizes in FC produced by mechanical foaming are smaller than those made by chemical foaming. The connectivity of pores depends on the density of the mixture, not on the foaming method. If the density reaches a level that allows the adhesive to separate individual bubbles, the pores tend to be closed. Otherwise, the FC will be dominated by the opening pore structures.

Hilal et al. [106] used scanning electron microscope (SEM) to characterize pore size and shape parameters, and then studied effects of different additives on strength performance. The investigation demonstrated that addition of additives notably enhanced microstructure and pore structure of FC slurry compared with conventional mixture. Though the additives increase the number of pores, higher strength was obtained due to the reduction of pore size and connectivity, which prevents pores from merging and producing a narrow distribution (see Figure 2). It is confirmed that FC strength not only depends on pore structure

Table 5: Pore features achieved by different foaming methods [26].

Foaming method	Diameter of pores (mm)	Volume of air voids	Shape	Density (kg/m^3)
Chemical foaming: gas release	0.5–3.0	15–65%	Spherical	Typical AAC: 300–800
Mechanical foaming: High shear mixing or prefoaming	0.1–1.0	10–50%	Less spherical, with shape factor 1.2–1.4	400–1600



(a) (b)

Figure 2: Effect of additives on cement paste microstructure, (a) with additive (more homogeneous) and (b) without additive [106].

enhancement, but also microstructure improvement of the cement paste.

Though many globally sourced literatures on FC have been documented, it is worth noting that research concerning performance enhancement from FC micromechanism should not be neglected, whereas microstructure signifies its various performance behaviors. The macroscopic aspect such as concrete type, filler, additive, foaming agent, and water cement ratio have been widely studied. However, there are very limited literatures on FC microstructure, so this may be a direction for future efforts to improve FC performance.

2.4. Stability. Stability is a major concern in FC. The stability of FC can be defined as a mixture with small, uniform, closed pore structure after hardening and no bleeding and segregation [167]. The stability of the experimental mixture can be evaluated by comparing (i) the calculated and actual quantities required to achieve a plastic density within 50 kg/m^3 of the design value and (ii) the calculated and actual water cement ratio [38]. The stable foam concrete mix depends on many factors viz., density, foaming agent, water to cement ratio, admixture, aggregate, and admixture.

2.4.1. Influence of Density. The stability characteristics of FC were studied by Jones et al. [168], and they found that concretes with a density of less than 500 kg/m^3 are more likely to be unstable. Also, replacement part Portland cement by compatible calcium sulphoaluminate (CSA) cement can produce stable low density mixture. Another study by Jones and McCarthy [138] showed that the instability of FC seems to almost inevitable at a very low density (less than 300 kg/m^3).

2.4.2. Influence of Foaming Agent. Lower concentration of foaming agent exerts a positive effect on the stability of FC [169]. The study by Ghorbani et al. [170] comparatively analyzed the effects of magnetized water on the stability of the synthetic-based and protein-based foaming agents. The results showed that magnetic water presents a positive effect on the stability of synthetic foam, but has an adverse effect on the stability of protein foam. Siva et al. [171] developed a green foaming agent from the natural soap fruit. It could be used as a substitute of synthetic foaming agent, which meets the existing ASTM foaming agent standard. The mixture with high foam content tends to be unstable after pouring, which hinders the development and use of low density FC. Experimental studies showed that severe instability was observed in some high foam content mixtures [172]. The instability could be easily found in the mixture sample when the foam content is over 0.61 m^3, showing an increase in instability with the increase of foam content. The results in experiments by Adams et al. [173] confirmed that the foaming agent with 5 wt.% binder can stabilize the FC at a density of less than 200 kg/m^3. Meanwhile, the pore structure of protein foam concrete is more uniform than that of tenside-based foam concrete. Sun et al. [44] studied the stability and workability of FC prepared with synthetic surfactants, animal glue/blood based surfactants and plant surfactants. They stated that, as a stable nanoparticle foam, synthetic surfactants foam shows the higher stability and air strength than those observed in the other two foams, which is advantageous to improve the performance of FC.

2.4.3. Influence of Mix Ratio. The results of the study by Ghorbani et al. [100] indicated that magnetized water can benefit the stability of FC. For the same mix proportions, the FC specimens with magnetized water show the higher stability than the control samples prepared with regular tap water because of the higher hydration degree. It is reported that the consistency of the base mixture added to foam exhibits a notable influence on the stability of the mixture. The spread flow of 45% in workability value is recommended to produce FC mix in good stability. The water to solid ratio required for producing stable mixtures increases with the addition of fly ash [168]. The adhesion force between particles and bubbles in the base mixture will enhance the stiffness of the mixture. The air foams may affect the stability of the mixture during mixing process, but this could be prevented by employing the higher water-solid ratio [167]. The volume instabilities of cement paste could suffer from the large water binder ratio [103]. Researchers proposed different methods for evaluating the stability of FC mix: (i) density of fresh foamed concrete was compared with its target density, and (ii) the difference between calculated and actual water cement ratio was checked and keep them close to 2% [88].

2.4.4. Influence of Admixtures and Aggregates. For concrete with a density up to 400 kg/m^3, 100% Portland cement can form a stable mixture. However, for the concrete with a density less than 400 kg/m^3, it is required to replace 5% to 10% cement with the compatible calcium aluminate cement so as to obtain stable FC [168]. Cong and Bing [174] pointed out that the addition of silica fume can improve the thermal insulation performance and strength and produce more uniform distribution pores. Though the use of quicklime helps in significantly increasing the density and strength of FC, reduction on the foam stability was observed.

2.4.5. Influence of Additive. The strength improvement and collapse prevention on high-performance FC are both helped by the addition of superplasticizer and a moderate reduction on water cement ratio [166]. In another study, the stability of FC with use of superplasticizer was improved by 43% when the water binder ratios were set less than 0.3 [168]. Qiao et al. [175] studied the applicability of gemini surfactant as novel air entraining agents for FC. The results showed that gemini surfactants have more stable air entraining capacity and higher surface activity compared to the current standard surfactants used in industry. The gemini surfactants modified with sulfonic groups have the notable stability, air entrainment performance, surface activity, and foaming properties. The use of water reducer to improve the performance of base mix is very effective for improving the stability of FC mixture. The addition of plasticizers increases the workability of the base mix and prevents mixture with foam content of 63–80% from collapse. The additives in FC produce less stress on the pores, which makes the cement slurry flow more easily between the neighborly pores. This is helpful to lead to a more uniform distribution of cement slurry in pores, reducing the coalesce and increasing the size of pores [172].

Some nano particles, such as nano silica or nanotubes, are always introduced to modify interface between bubbles and cement paste [176]. These nanoparticles gathering at gas-liquid interface helps to reduce the contact area between bubbles and forms a dense particle film to restrain the coalescence and disproportionation of these bubbles. At the same time, a three-dimensional network structure will be formed between the foam surface and the continuous phase, which is advantageous to prolong the drainage time of the liquid membrane [177]. A schematic representation of three-phase-foams after foaming reported by Krämer et al. [178] is shown in Figure 3.

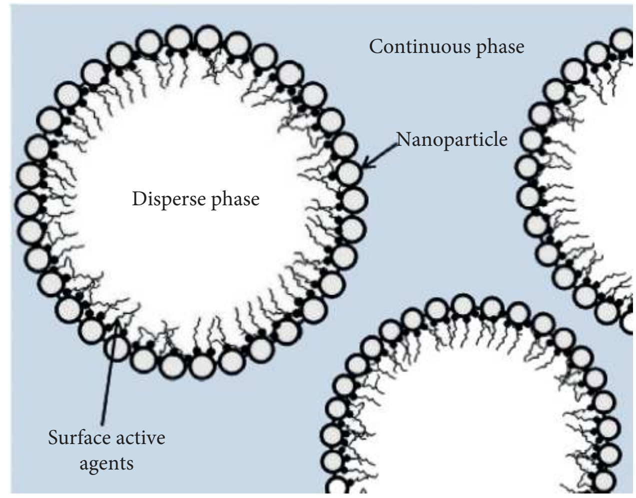


FIGURE 3: Diagrammatic sketch of three-phase-foams after foaming [178].

Researchers reported that even though nanoparticles are not amphiphilic, most of them are surface active [179]. The hydrophobicity of particles is regarded as a key factor to assess whether the particles could be adsorbed and remained around bubbles. Binks and Horozov [179] modified the silica surface with silanol groups and made it to exhibit different extents of hydrophobicity for the purpose of the investigation on foam stability. The results suggested that the surface contents of SiOH varying from 30% to 50% are advantageous to produce foams with good stability and large foaming capacity. Also, an increase of pH value or a reduction of NaCl concentration caused the foams turning from stable three-phase state into unstable two-phase state. Gonzenbach et al. [180] employed short-chain amphiphiles such as carboxylic acids, alkyl gallates, and alkylamines to modify the surfaces of nano silica and nano alumina. In this way, nanoparticles can be adsorbed on the surface of bubbles by chemical bonds so as to produce super stable low-density foams [181].

However, the foams produced by combining nanoparticles with surfactants are not always stable, instead, they sometimes promote the bubble's disappearance. The adsorption of nanoparticles on the bubble surface will accelerate the seepage velocity of the liquid film. The connection of the liquid films and bubbles leads to the burst of the bubbles. Of course, the stability of foam in this situation could be improved by the use of the suitable nanoparticles and surfactants [182]. Tang et al. [183] pointed out that the hydrophilic silica particles combined with sodium dodecyl sulfate (SDS) in FC exhibit a positive foam stabilization effect, whereas the addition of nano silica leads to reduction of bubble size. In another study, Alargova et al. [184] reported that the stability of the foams produced by combined use of the SDS and bar polymer particles is lower than that observed in single-particle stabilized foams. In another study, Binks et al. [185] revealed that the stability of bubbles formed by the mixed system of SiO_2 and cetyltrimethylammonium bromide (CTAB) was significantly higher than that in the single CTAB system, but the foaming property was slightly weaker. This is because some CTAB was adsorbed onto the surface of the nanoparticles, which increases the hydrophobicity degree of the nano silica. The stability of the foam system was improved, but, at the same time, the foaming capacity was reduced as a result of the reduction in the concentration of the foaming agent in the solution.

2.5. Enhancement. Even though FC has been widely used in nonstructural components, the applications in structural members are still limited due to its strength issue. It is reported that the insufficient strength of FC is mainly because of the uneven distribution of internal pore size. It is easy to lead to stress concentration in small pores under action of the loads, resulting in the destruction of FC. The influence of pore size distribution and pore distribution uniformity on the properties of foam concrete is well known [115, 118]. Thus, it is essential to minimize the coalescence of bubbles and improve the numbers of small pores and closed pores in foam concrete.

Researchers have made different attempts in order to strengthen FC. Now, the addition of fibers is the most commonly used method to improve the mechanical properties of FC [73, 74]. An investigation by Falliano et al. [92] stated that 0.7% fibers mixed in FC did not seem to notably improve mechanical strength compared with the reference sample without fibers. It is observed that the flexural strength was significantly improved when increasing the fiber content to 5.0%; however, there is no obvious improvement in the compressive strength was recorded. Especially, the improvement of flexural strength mainly depends on the dry density and is less affected by curing conditions. Dawood and Hamad [75] studied reinforcement effect of glass fibers (GF), polypropylene fiber (PPF), and hybrid fibers (GF + PPF) on the toughness behaviors of high-performance lightweight foam concrete (HPLWFC). The results showed that the use of glass fiber increases the compressive strength, whereas the addition of polypropylene fiber reduces the compressive strength of the HPLWFC. The greatest increment on the compressive strength of the HPLWFC is observed in the experimental species with 0.4% glass fibers and 0.6% polypropylene fibers. Experimental results by Hajimohammadi et al. [105] confirmed that use of Xanthan gum (XG) as a thickening agent significantly affects the viscosity of the foam solution and condensates the liquid film around the foams. The drainage and collapse of the prefoaming materials can be greatly reduced with the increase of XG concentration, notably improving the predictability and controllability of the chemical foaming. XG modified samples have smaller and narrower pore size distribution compared to the control sample, which has a positive effect on the thermal conductivity and compressive strength of the specimens.

The control of bubble size has an effect on the performance improvement of FC. Xie et al. [104] pointed out that improving the pore forming method, reducing the size of bubbles and increasing the nanopores in foam concrete have become the key issues for FC research. For the same density, the porosity decreased gradually with the increase of bentonite slurry content, resulting in an increase of wall thickening between pores. The pore size decreased with the increase of bentonite slurry from 0% to 50%, the average pore size decreased significantly, and the pore size distribution was narrower. The gas in the small bubble enters the large bubble through the liquid film to balance the pressure, so that the bubble is distributed in a large range. The thicker water lubrication film between bubbles restricts the gas exchange of mixture with low precast foam dosage, resulting in uniform pore size.

Jones et al. [168] reported that unstable behavior of bubbles causes the uneven pore size distribution in FC. The combined action from the buoyancy, gravity, slurry pressure, and internal pressure result in instability in bubbles when the bubbles are introduced into the cement paste. The smaller the bubble, the more prominent the instability. This unstable state in bubbles leads to the continuous fusion and growth of bubbles, which makes the bubble size larger. The bubble fusion behaviors are more obvious when a larger amount of foams is used. Also, due to the small amount of slurry, the pressure of the slurry on the bubble becomes smaller and the bubble floats up, which leads to surface settlement and collapse of FC.

Currently, a new way to further improve the performance of FC is introducing the three-phase-foams, which is helpful to weaken the instability by reducing the high interfacial energy and free energy of the system [176]. A study by She et al. [186] made use of the coupling of organic surfactant and nanoparticles to change the gas liquid interface so as to produce super stable foams for FC production. A separation effect between bubbles and fresh cement paste works when the bubbles are added into the cement paste. These bubbles will be balanced under the action of various forces consisting of bubble limiting force (F_c), the gravity (F_d), the internal bubble pressure (P_i), and surface tension (F_{st}) as well as bubble buoyancy (F_b) induced by surfactant effect, as shown in Figure 4.

The instability of the bubbles in normal foams is mainly attributed to the drops of F_{st} and F_c; therefore, these bubbles grow easily and float to the upper region of the slurry under action of the F_b. An undesirable matching between the forces acting on the bubbles and early strength limits the bubble motion, leading to the stratification and uneven density in the foam concrete.

On the contrary, this situation was improved when the bubble surfaces were modified with the addition of nano silica (NS) particles, and the films were enhanced with hydroxypropyl methylcellulose (HPMC). These NS particles increase the surface roughness and the friction drag of the bubbles moving in the cement paste, while the free energy on the bubble surface is absorbed by the NS particles.

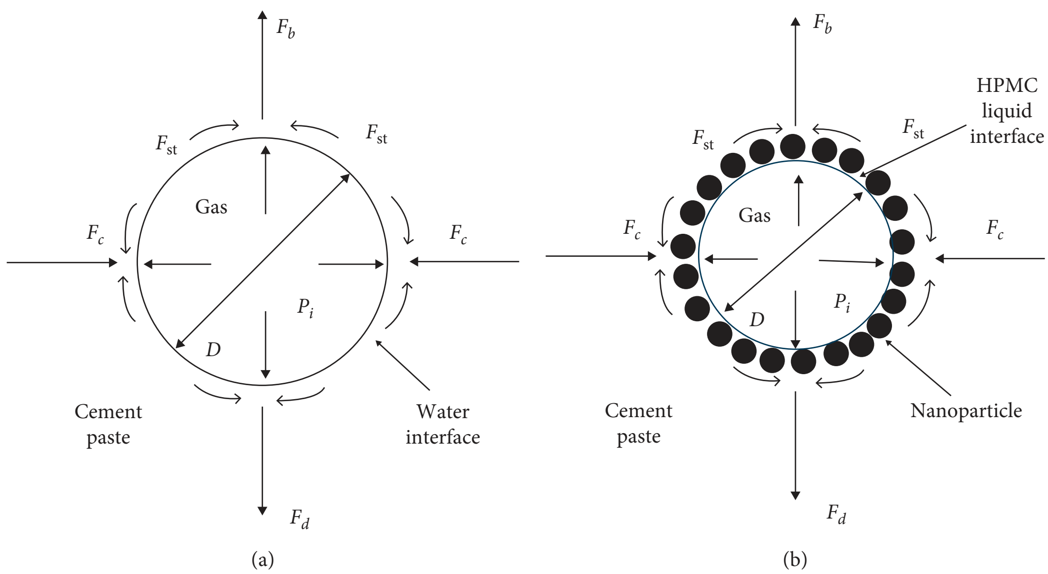


FIGURE 4: Forces acting on (a) a normal bubble and (b) a nanoparticle stabilized bubble [186].

In addition, the use of carbon nanotubes as reinforcement components in cement-based materials has attracted a lot of attention. The structure and performance modification in FC can be realized by dispersing the multiwalled carbon nanotubes in foam concrete [187]. The most significant improvements in carbon nanotube-based FC are observed in the mechanical properties [188, 189]. The addition of carbon nanotubes not only improves the performance of the FC, but also ensures the uniformity of pore size. The dispersion of carbon nanotubes leads to a fine structure of the cement paste which results in dense concretes [188, 189]. A more uniform and compact cement paste is achieved by the effect of calcium hydroxide crystallization. Meanwhile, a higher amount of C-S-H in hydration of concrete is observed because carbon nanotubes play a role in the formation of C-S-H phases [190]. The strengthening is also provided even with a small amount of 0.1% w/w carbon nanotubes related to binder content. It is also reported that the use of carbon nanotubes with low mass content in nonautoclaved concrete reduces its thermal conductivity and improves the mechanical properties [189].

Krämer et al. [176, 178, 191–193] conducted a series of investigations on strengthening of FC by introducing nanoparticles (nano silica, carbon nanotubes) for the purpose of stabilizing the foams. The findings proved that the mechanical properties and bubble structures are both generally improved compared to normal foam concrete. The nanoparticles encapsulating on the foam surface participate in the hydration of the cement, thereby increasing hydration products and enhancing the strength of cellular walls of FC.

A novel method adding pozzolanic active nanomaterials into concrete for reinforcement was put forward recently [193]. The produced foam concretes have higher compressive strength than those observed in industrial FC without needs of further optimization or other enhancement means. These concretes show possibilities to provide comparable properties with industrial lightweight concretes in the future. The foam concretes exhibited a specific formation of hydration products and a shell-like pore structure. Also, the pore size distribution of the FC was under control due to the use of three-phase-foams.

The findings in [176] confirmed that decrease of pore size can be observed by making use of the three-phase-foams, but the wider pore size distribution was observed with adoption of nanotubes. It is also reported that the three-phase-foams combining with other nanomaterials or the obtained approaches can further improve the properties and performance of FC.

3. Practical Application of FC in Tunnels and Underground Projects

3.1. Significance and Benefits. The FC has been gradually regarded as a renewed material to address problems faced in tunnels and underground projects. FC performs well with the excellent mechanical properties compared to the ordinary concrete (OC), and some comparisons are presented in Table 6. It is expected to be partially or completely substituted for conventional concrete in underground engineering, providing with economic, social, and environmental benefits.

3.1.1. Excellent Properties. The extensive properties variations of FC are applicable for various situations. Low density (generally from 300 to 1800 kg/m^3) helps to reduce dead load without producing lateral load [26, 28]. A large number of closed small pores containing in FC are responsible for its outstanding fire resistance [206], low thermal conductivity and sound insulation properties [174, 207], which are not available in OC. The FC with a density varying between 300 and 1200 kg/m^3 usually has a thermal conductivity value of 0.08–0.3 W/mK [36, 208]. As a result of light weight and low modulus of elasticity, the FC-reinforced structures exhibit considerable aseismic capability by effectively absorbing and

Table 6: Tabulation presents properties comparison between OC and FC [36, 107, 131, 167, 194–205].

Type	Physical: Dry density (kg/m^3)	Physical: Drying shrinkage (%)	Physical: Porosity (%)	Mechanical: Modulus of elasticity (GPa)	Mechanical: Compressive strength (MPa)	Mechanical: Tensile strength (MPa)	Mechanical: Flexural strength (MPa)	Functional: Thermal conductivity (W/m K)	Functional: Fluidity (mm)
OC	2000–2800	0.05–0.1	—	25–38	15–80	0.9–2.5	2.0–9.0	ca. 2.5	ca.190
FC	300–1800	0.15–0.35	0–84	0.1–1.0	0.6–43.0	0.05–0.55	0.03–0.9	0.05–0.3	>180

diffusing shock energy when subjected to the seismic loading. The properties promote the application of FC in tunnel, and underground engineering can be revealed from (1) low self-weight, (2) free flowing and self-leveling, (3) load spreading, (4) insulation capacity, (5) reliable quality control, and (6) freeze and thaw resistance.

3.1.2. Environment Friendly. It is desirable to utilize recycled waste such as fly ash and recycled glass in FC production so as to protect the environment pollution [209]. The main raw materials required for FC are cement and foaming agents. The majority of the foaming agents are nearly neutral surfactants with considerable biodegradability, in which benzene and formaldehyde are usually not contained. Therefore, soil, water, and air are faced with little adverse impacts [210–212], whereas FC can minimize disruption to natural environment during construction phase.

3.1.3. Cost and Time Saving. It could be an economically viable solution, particularly in large-volume applications. Excellent fluidity and self-leveling mean less requirement for energy consumption and manpower moving by using pipes for pumping [213]. On the premise of ensuring FC strength, a large number of industrial wastes can be used as fillers [214]. Therefore, lower investment for FC application is usually attributable to tailored mix design, rapid equipment installation, and cost decrease in maintenance.

3.1.4. Repaid Construction. Pumping FC can be realized by equipping with foam mixer, power pump, and conveying pipeline in a workload of 200–300 m^3/d within the theoretical vertical height and horizontal distance of 200 m and 600 m, respectively [215]. A considerable pumping capacity is usually not required as a result of the high fluidity of FC, while mass production and placement are always based on a continuous operation so as to notably improve work efficiency. Also, only limited deliveries for raw materials are needed because the foam acts as the largest volume contributor in FC.

3.2. Novel Application in Tunnel Engineering

3.2.1. Thermal Material. In the present years, thermal measures for cold-region tunnels mainly include electric heat tracing, thermal insulation door, and antifreeze thermal insulation layer (i.e., thermal insulating materials laid on liner structure) [216–218]. However, the electric heat tracing needs a lot of energy resources to ensure thermal efficiency, which slightly deviates from the increasingly demanding requests from the perspective of energy saving of constructions. The thermal insulation doors are not suitable for tunnels with large traffic volume, resulting in sizable heat loss owing to incessant opening and closing [219, 220]. Hence, using FC as liner structure and insulation material is helpful to simplify construction process and reduce material costs.

A case study using FC as insulation material in a tunnel in the Tibet, the Alpine Region of China, was reported by Yuan [221], where frozen period with the minimum temperature of −27.7°C lasts eight months every year. Table 7 presents the optimum mix proportion of FC used in the study. The temperature in the measured positions without insulation layer varies significantly compared to location that with insulation layer. The results indicated that temperature change and the minimum temperature in these two locations are 4.5°C, 2°C and 1°C, 3°C, respectively. The findings regarding impacts of freeze-thaw cycles on FC performance [44, 222] will be helpful to further improve and optimize the durability of FC used as insulation materials.

3.2.2. Aseismic Layer. The aseismic layer is generally placed between rock and tunnel liner in order to transfer some of rock mass pressure during construction period so as to avoid liner damage when it is subjected to earthquake action [223–225]. The considerable load-bearing and deformation capacities promote it to be an ideal aseismic material in tunnel engineering. As shown in Table 8, Zhao et al. [226] developed a new aseismic FC material and then applied it in Gonggala tunnel of China. The numerical analysis results showed that this new FC-based material significantly reduced stress and plastic zones in tunnel liner. Meanwhile, an investigation conducted by Huang et al. [227] revealed that using FC as aseismic material is superior to rubber through the durability tests.

3.2.3. Structure Member. Creep deformation in tunnels especially for deep ones will continue after completion of secondary liner [228–231], which easily causes structure damage or failure. Simple increase in secondary liner thickness cannot completely control the creep deformation in rock mass. FC-based members embedded between primary support and secondary liner can notably bear deformation pressure, thereby the high compressibility and

Table 7: Optimum proportion for tunnel antifreeze layer (percentage content) [221].

Material	Fly ash	Perlite	Foam	Polypropylene fiber	Water	Water-proofing additive	Antifreeze additive	Water reducer	Coagulation accelerator
Ratio	30	18	150	0.2	40	0.3	2	1	4

Table 8: Tabulation shows mix proportion of FC used for aseismic isolation layer (unit: kg/m^3) [226].

Material	Cement	Foam	Perlite	Water	Water-proofing additive	Antifreeze additive	Water reducer	Coagulation accelerator	Fibre
Ratio	600	0.8	108	250	5	13	6.5	30	1

ductility of FC can help to eliminate overall damage or failure. The FC with compressive strength of 0.4–0.7 MPa, porosity of 68%, and density of 800 kg/m^3 [232] was adopted in liner system of Tiefengshan No. 2 tunnel to resist gypsum-salt-induced swelling pressure. Since successful implementation in September 2005, the tunnel has been running well, and no damages have arisen.

Wang et al. [233] studied long-term performance of FC-based liner member with a comparison to common large-span soft rock tunnel, the findings showed that after creep for 100 years, vault settlement and horizontal convergence reduced by 61% and 45%, respectively, while plastic zone in secondary liner was obviously decreased. Wu et al. [234] developed a special yielding support system combined with a new type of FC. This newly developed system was embedded between primary support and secondary liner. The results confirmed that the plastic zone and deformations at the roof and the sides of the secondary liner were significantly reduced as a result of cushion effect, compared to stiff support system.

3.2.4. Backfill and Reinforcement. Table 9 summarizes practical applications of FC used as selective filling material in road tunnels. Specifically, the filling cases mainly include space or cavity fill, open-cut and auxiliary tunnel backfill, bulk fill such as disused tunnel backfill, collapse treatment, etc. And some typical applications are described as follows.

Kontoe [240] reported a backfill case in the Bolu highway twin tunnel repair in Turkey (Figure 5(a)). The tunnel suffered extensive damages during the 1999 Duzce earthquake, and a large amount of FC was temporarily backfilled to stabilize tunnel face during reconstruction activities. The excellent priorities compared to OC give rise to FC application in tunnel collapse treatment. The controllable density and strength as well as good liquidity can fill and then saturate collapsed cavity entirely, thus consolidating fractured body. Figures 5(b) and 5(c) present photos of using FC to reinforce a 20 m long and 9.6 m deep collapse body in Shima tunnel, where rock mass was broken and cut obliquely [241]. The subsequent feedbacks from construction site verified the effectiveness of this treatment material.

3.2.5. Dead Load Reduction. Figure 6 illustrates FC application for load reduction while raising ground to a required level that commonly used in metro system. Recently, FC production in Europe, North America, Japan, Korea, China, and Southeast Asia has been the matured technologies. Other forms for the usages of FC include selective fill and reinforcement for safe construction.

3.3. Novel Application in Underground Engineering

3.3.1. Underground Coal Mine Roadway. The FC applications in coal mines are mainly summarized from three aspects: backfilling materials, support system, and water/harmful gas blocking, which are presented as below:

(1) Backfill Material. As early as 1992, the United States Bureau of Mines had released the programmer of using FC at a density of 720 kg/m^3 to backfill abandoned mines, and the target used for field construction was No. 22 mine in Logan County, West Virginia [242]. And the world's largest single use of FC in mine by far is the stabilization work of Combe Down Stone Mines near Bath of the UK, which eventually used about 400,000 m^3 FC at density and strength of 650 kg/m^3 and 1 MPa, respectively (Figure 7) [243].

(2) Support System. Tan et al. [244] put forward a composite support system containing FC damping layer in view of the large deformation in soft rock roadway of coal mine. The results showed that shrinkage of U-shaped steel significantly decreased as the FC absorbs the most of the generated deformation (Figure 8).

(3) Water/gas Blocking. The airtight walls in coal mines are considered to be an effective method to prevent residual coal from spontaneous combustion caused by air leakage. In a study by Wen et al. [245], a new type FC was developed for yielding a wall to control potential air leakage. The 28 d compressive strength of the FC wall reached 5 MPa, in which no remaining fissures were observed; therefore, it effectively suppressed air leakage to the gob (Figure 9).

3.3.2. Public Pipelines and Facilities. Practically, utilizing FC materials for municipal pipelines backfill helps to control postconstruction settlement caused by poor compaction. In Japan, municipal pipelines such as gas pipelines are always filled with FC so as to prevent external damage, especially in areas where earthquakes occur frequently [246].

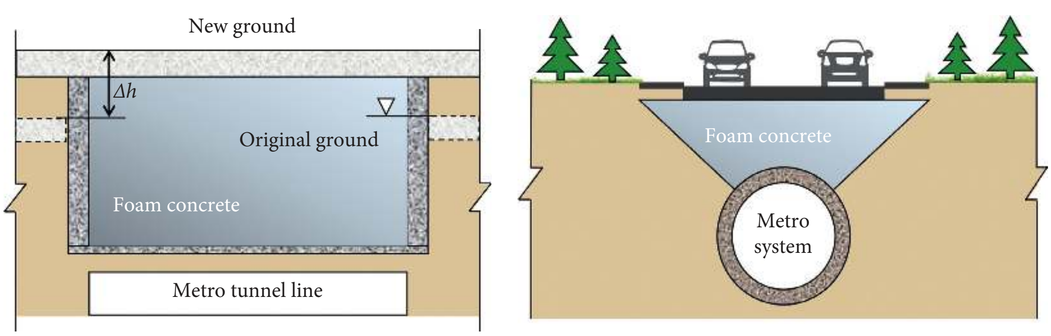
FC has been expected to use in hydraulic tunnels to resist damages during earthquakes struck. Dowding and Rozen [247] confirmed a series of seismic damage events on hydraulic tunnels in USA by statistical analysis on dozens of

Table 9: Application examples of selective fill with FC.

Reference	Tunnel name	Country	Year	Application	Brief descriptions
[235]	Kent Thameside tunnels	UK	2010	Reclamation	The 50 m deep tunnel extends about 90 m, and FC with density of 400 kg/m^3 and compressive strength of 0.5 MPa was backfilled.
[236]	Dakota Project	USA	2000	Reinforcement backfill	The original granular backfill above the tunnel resulted in foundation foot settlement and finally caused structure deformation. The original filling was removed and replaced by 500 kg/m^3 FC.
[237]	Farnworth	UK	2015	Auxiliary construction	The 7800 m^3 FC of 1100 kg/m^3 and 1 MPa was used to backfill the one of a 300 m long double-hole tunnel so as to accept the Tunnelling Boring Machine (TBM).
[235]	Thackley	UK	2013	Structural reinforcement	As more distortion was recorded, with the crown being forced upwards into a void. A total 2540 m^3 FC with 1120–1130 kg/m^3 and 1 MPa was required for fillers.
[238]	Huashiya	China	2015	Cavity filling	Cavities and cracks appeared in secondary liner of tunnel, and then these defects were filled by FC grouting.
[235]	Gerrards Cross project	UK	2009	Load reduction	To reduce dead load, pile walls were installed on both sides of the tunnel, and 26,000 m^3 FC with 375 kg/m^3 was used to form horizontal ground at the top of vault.
[239]	Wulaofeng	China	2009	Seepage water treatment	The seepage of tunnel side wall was serious, and some locations were even gushing, so FC was used as waterproof material.

(a) (b) (c)

Figure 5: (a) Bolu highway twin tunnel [240], (b) collapse, and (c) treatment with pumped FC in Shima tunnel [241].



(a) (b)

Figure 6: FC application in metro system.

case tunnels. The similar seismic hazards were also be documented in Japan during the 1995 Osaka–Kobe earthquake ($M_s = 7.2$), in which water supply pipelines and sewage drainage systems in Hanshin and adjacent areas were severely damaged. The water supply systems in Kobe were even completely destroyed [248, 249]. Currently, many contributions have been made to use FC as antiseismic material in hydraulic tunnels. The Port Mann Water Tunnel Project, located in Vancouver, Canada, was constructed with a total 6000 m^3 FC to meet a seismic backfill requirement for 100-year reliability [250].

4. Thoughts and Future Work for Popularization of FC

4.1. Emerging Direction for Performance Enhancement of FC. Though a lot of research has been carried out focusing on macroscopic properties of FC, such as thermal conductivity, mechanical properties, water absorption, etc., the studies on drying shrinkage, bubble size control, stability, and pore structure characterization are still insufficient.

Ghorbani et al. [110] used scanning electron microscope (SEM) to study FC microstructure. The results showed that

Figure 7: Combe down stone mines (source: http://www.foamedconcrete.co.uk).

Figure 8: A composite supporting system containing FC [244].

(a) (b)

Figure 9: Filling effect of FC wall after (a) 24 hours and (b) 28 days [245].

the FC microstructure was notably improved by using magnetized water instead of conventional tap water. The FC structure with magnetized water has a lower porosity and is denser than that with conventional tap water. Using magnetized water in FC increases its stability and compressive and tensile strengths as well as reduces the water absorption.

The FC microstructure filled with silica fume was studied by Reisi et al. [251]. The SEM and X-ray diffraction tests showed that the reaction between silica fume and free calcium hydroxide in hydrated cement generates the hydrated calcium silicate. Its hardness and durability are higher than calcium hydroxide so as to reduce the risk of sulfate attack in silica fume FC. Consequently, the hydrated calcium silicate produced homogeneous FC with better solid and pore distribution, which leads to a higher compressive strength compared to FC without silica fume.

The X-ray microCT imaging results reported by Chung et al. [252] confirmed that the shape and size of pores and local density of the solids have remarkable impacts on performance and damage mode of FC, which has profound guiding significance for high-performance FC production. In addition, Zhang and Wang [128] confirmed that pore size notably affected the compressive strength of glass-fiber-reinforced FC, especially at a high porosity. The pore shape maintains relatively constant as a result of the function of foam content and density variation, which does not bring about much effect on mechanical properties of FC.

There are relatively few studies on FC microstructure such as shrinkage mechanism, shrinkage prediction, strength improvement, etc. To be sure, all of the above-mentioned studies are helpful to deeply understand durability issues; therefore, linking the microstructure and macro-performance of FC in order to better enhance its performance should be deeply investigated.

4.2. Technical Limitation. Dramatically, the mix proportions of FC have always been the technical challenge and one of the research hotspots. So far, there are no clearly defined methods to determine the mix proportion despite some experimental-based and error-based methods can be used. Recently, Tan et al. [8] proposed an equation for mix proportion determination:

$$\begin{aligned} \rho_d &= S_a M_c, \\ V_2 &= K(1 - V_1) = K\left[1 - \left(\frac{M_c}{\rho_c} + \frac{M_w}{\rho_w}\right)\right], \\ M_y &= V_2 \rho_f, \\ M_p &= \frac{M_y}{\alpha + 1}, \end{aligned} \tag{2}$$

where ρ_d is the dry density of the designed FC (kg/m^3), S_a is the empirical coefficient, M_c is the mass of cement (kg/m^3), V_1 and V_2 are the volume of cement paste and foam, respectively, ρ_c and ρ_w are the densities of cement and water, respectively, M_c and M_w are the cement and water, respectively, K is the coefficient, M_y and ρ_f are the mass and density of foam, respectively, M_p is the mass of foaming agent, and α is the dilution ratio.

Practically, water quality, cement, lime, and other aggregates worldwide are characterized by unique features and the technical level for fiber preparation varies greatly. The optimum mix proportion of FC will also be affected by regional environments [253]. Hence, it is necessary to determine the best mixing proportion under different regional tests, avoiding using existing mix proportion schemes directly. This challenge may be one of the important factors restricting worldwide applications of FC in tunnel engineering [254–256].

Develop cheaper foaming agents and generators are also urgent tasks to promote practicality and wider application of FC. The compatibility between foaming agents and various admixtures should be studied to strengthening FC. Meanwhile, to reduce water demand and shrinkage, in-deep study on compatibility of chemical admixtures is required. The difficulties encountered in FC production such as mixing, transportation, and pumping also need to be solved, whereas they exhibit significant impacts on freshness and hardening properties of FC [64].

4.3. Government Support. Regarding as a kind of green construction material, FC accords with increasing demands of sustainable perspective of construction for countries worldwide. The booming development of infrastructures has increased the demands for various new environmental protection materials, in which the FC plays a key role. With the government support, whether the policy or economic aspect, the more scientific research outputs from universities, research institutes, and enterprises will be obtained, which is conducive to enhance establishment and reform of the relevant industrial systems, thereby alleviating consumer concerns.

4.4. Other Considerations. Lack of the complete production data and construction experience makes it difficult to form the complete construction systems. Therefore, establishing the reliable design and construction procedures for FC usage is helpful to overcome the construction difficulties. Moreover, relevant specifications, codes, and standards should be implemented timely so as to standardize the design and construction processes of FC.

5. Conclusions

Based on the review conducted, it was observed that most of the studies on FC have been conducted to the evaluation of its properties rather than on the foam features, which has impacts on the strength and enhancement of the foam material. According to the findings provided by researchers, the following conclusions are drawn from extensive literature review:

(1) To enhance FC performance and popularization, the relevant properties were elaborated and some aspects were proposed as constraints for wider application of FC such as drying shrinkage, strength issue, stability, enhancement, and long-term durability.

(2) Foam stability is a significant aspect which significantly affects the strength of FC. Production of the stable FC requires to consider many factors such as the method of preparation of foam, type of foaming agent, the accuracy of the mixture, type of surfactants and additives used, usage of nano particles and mix design, etc.

(3) Very few studies on durability of FC are available. Durability properties of FC mainly influenced by the ratio of connected pore to total pore. The FC with uniformly distributed closed circular air pores exerts good thermal and mechanical properties.

(4) Current research mainly focuses on the microscopical characterization of FC and the impacts of the several factors on the physical, mechanical, and functional performance. However, very limited literatures have put emphasis on systemic microstructure characterization of FC.

(5) The use of three-phase-foams instead of wet foams based on surfactants or proteins and water for improving the performance of FC has been renewed interests because the incorporation of three-phase-foams in cement paste is advantageous to stabilize the pores and control the pore size distribution.

Conflicts of Interest

The authors declare no conflicts of interest.

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