Review

A Review on Durability of Foam Concrete

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Abstract: Foam concrete is a promising material in building and construction applications, providing such outstanding properties as high specific strength, excellent thermal insulation, and effective acoustic absorption in human-inhabited buildings. However, because the porosity and permeable water absorption properties of foam concrete are significantly higher, its durability is often not comparable to that of ordinary concrete, and so the durability of foam concrete requires significant attention during the life cycle of building applications. Durable materials can greatly reduce the environmental impact of waste from maintenance and replacement and the consumption of natural resources resulting from the production of repair and replacement materials. After hardening, the durability of foam concrete includes freeze-thaw cycle resistance, elevated temperature resistance, carbonation resistance, efflorescence resistance, sulfate resistance, chloride resistance, alkali-silica reaction, and so on. This paper reviews articles on the durability of ordinary Portland cement (OPC) foam concrete, geopolymer foam concrete (GFC), magnesium phosphate cement (MPC) foam concrete, sulphoaluminate cement (SAC) foam concrete, and limestone calcined clay cement (LC^3) foam concrete and compares their durability to provide a reference for the life cycle design and service life estimation of foam concrete members.

Keywords: foam concrete; freeze-thaw cycle; elevated temperature; carbonation; efflorescence; resistance to aggressive environments

1. Introduction

Concrete exposed to harsh conditions undergoes a variety of deterioration processes, reducing its ability to maintain serviceability, quality, and initial form; this is defined as the durability of concrete [1]. Although durability problems in materials may not immediately cause safety issues for components and structures, potential threats to the maintenance of their serviceability will gradually accumulate and eventually cause safety issues. In order to eliminate this problem, many researchers have conducted in-depth research on the durability of normal concrete, proposing some feasible design methods and guidelines based on durability [2–4].

In the past few decades, building energy conservation and emissions reduction have been paid growing attention [5]. Foam concrete, as an inorganic insulation material, has drawn increasing interest in efforts to lower building energy consumption. Although foam concrete offers positive properties as a building insulation material [6], its use in North America, Australia, Europe, and Africa is really low [7], mainly due to certain concerns and insufficient awareness in relation to the durability of foam concrete in various environments. In order to allow the wide use of foam concrete in various environments, this paper reviews the durability characteristics of the freeze-thaw cycle resistance, elevated temperature resistance, carbonation resistance, efflorescence resistance, acid resistance, sulfate resistance, chloride resistance, and alkali-silica reaction of OPC foam concrete, GFC, SAC foam concrete, MPC foam concrete, and LC^3 foam concrete to eliminate durability concerns.

2. Freeze-Thaw Cycle Resistance

One of the durability problems of concrete in its life cycle application is freeze-thaw cycle resistance. During the freeze-thaw process, water enters the concrete and expands under freezing conditions, creating stress; at a certain temperature, the ice then melts into water. In multiple freeze-thaw processes—namely freeze-thaw cycles—concrete tends to suffer such damage as crack formation, mass loss, increased porosity, and decreased mechanical properties [8]. It has been reported [9] that, compared with ordinary concrete, foam concrete has superior freeze-thaw cycle resistance. This is because the freeze-thaw damage of ordinary concrete is caused by the freezing expansion of water in the capillary pores. However, due to the large pores present in foam concrete, if the water in those pores is not saturated, and even if the water freezes and expands in the larger pores, no freeze-thaw damage will occur [9,10]. Therefore, foam concrete with a well-designed pore system will enjoy better freeze-thaw cycle resistance [11].

It is very important to test and evaluate the freeze-thaw cycle resistance ability of foam concrete in order to maximize the longevity of foam concrete members. In terms of freeze-thaw test methods for foam concrete, the critical degree of saturation test [12,13], top surface freezing test [14], standard test for the resistance of concrete to rapid freezing and thawing in ASTM Standard C666 [15], and a modified freeze-thaw test method based on ASTM Standard C666 [16] have been developed and used to test and evaluate the freeze-thaw cycle resistance of foam concrete. The critical degree of saturation test and top surface freezing test have the disadvantage of not providing a complete method of freeze-thaw durability measurement, while ASTM Standard C666 fails to limit the moisture content of foam concrete during freeze-thaw cycles. Meanwhile, a modified freeze-thaw test method based on ASTM Standard C666 has provided favorable evaluation results with foam concrete.

In OPC foam concrete, freeze-thaw cycle resistance is reported to depend on the depth and rate of water absorption and the compressive strength of the foam concrete, but to have little relationship with permeability and density [16]. Dhir et al. reported that lower density foam concrete exhibited higher freeze-thaw resistance because larger pores could accommodate the expansion of water and osmotic pressure [17]. However, Shon et al. tested foam concrete for performance degradation after 60 freeze-thaw cycles (30 days) and reported that lower density foam concrete did not always possess higher freeze-thaw resistance [18]. Additionally, She et al. demonstrated that lower-density foam concrete with larger and more interconnected pore structures and weaker slurry had lower freeze-thaw resistance [19]. Indeed, the connectivity, size, and stability of the pores was much more closely related to the true impact of density on the freeze-thaw resistance of foam concrete [18]. It was claimed that increasing the quantity of consistently small (below 300 μm) air bubbles or air voids in foam concrete was essential for increasing its resistance to the freeze-thaw cycle [20]. It was also reported that foam concrete samples with an appropriate water-binder ratio have more closed pores and improve freeze-thaw cycle resistance [21].

The recycling of waste in foam concrete affects freeze-thaw cycle resistance, as shown in Table 1. Replacing cement with fly ash reportedly reduces the number of small pores in foam concrete, resulting in decreased freeze-thaw cycle resistance due to the low pozzolanic effect of the fly ash used and the unburned carbon in fly ash, which may affect the stability of smaller pores [18]. The freeze-thaw cycle resistance initially increased and subsequently declined with increased replacement quantity when fly ash (which has a relatively active pozzolanic action) was employed as a cement replacement [21]. Simultaneously replacing cement with lime and fly ash can enhance the freeze-thaw resistance of foam concrete due to the fact that lime promotes the hydration of fly ash, resulting in reduced pore size [22]. In addition, Zhang et al. [19] reported that the freeze-thaw cycle resistance of foam concrete first increased and then decreased with increased slag replacement (although the impact was not significant), while silica fume as a cement replacement had a considerable impact on freeze-thaw cycle resistance. Although a small amount of silica fume could

promote the volcanic ash reaction and physical pore filling effect and enhance freeze-thaw cycle resistance, after reaching the most suitable replacement amount, freeze-thaw cycle resistance gradually decreased with increased replacement amount [21]. Bayraktar et al. [23] and Gong et al. [24] also showed that the freeze-thaw cycle resistance of foam concrete rose initially and then declined with the increase in slag and silica fume replacement, respectively. Rice husk ash [25] and silt soil [26] (as partial replacements for cement) enhanced the resistance of foam concrete to the freeze-thaw cycle.

Table 1. The effects of various mineral admixtures and aggregate types on the freeze-thaw cycle resistance of OPC foam concrete.

Type of Materials	Cement Replacement Ratio (%)	Sand Replacement Ratio (%)	Variation In Freeze-Thaw Cycle Resistance	Reference
Fly ash	25	-	Decrease	[18]
	10–60	-	Increase	[21]
	4–28	-	Increase	[21]
Slag	30–60	-	Increase	[23]
	9–33	-	Increase	[24]
Silica fume	3–21	-	Increase	[21]
	2–9	-	Increase	[24]
Rice husk ash	10–16	-	Increase	[22]
Lime	10–20	-	Increase	[25]
Rice husk ash	20–40	-	Increase	[26]
Fly ash	-	50–100	Increase	[19]
Recycled waste marble powder	-	25–50	Increase	[25]
	-	100	Increase	[23]
Waste tire rubber	-	100	Increase	[27]
Expanded perlite	-	30–100	Decrease	[28]

When used as a substitute for fine sand in foam concrete, fly ash can more effectively reduce strength loss than fine sand as a fine aggregate, while fine sand can reduce mass loss more effectively than fly ash, because sand can limit surface spalling and water expansion. However, the inside of sand is more vulnerable to freeze-thaw cycle damage, while fly ash can improve the pore size and distribution of foam concrete [19]. Similar conclusions were reported by Hilal et al. [29,30]. Gencel et al. [25] and Bayraktar et al. [23] reported that foam concrete using recycled waste marble powder as a partial replacement for fine sand improved freeze-thaw cycle resistance. Moreover, the replacement of fine sand with waste tire rubber can also increase freeze-thaw cycle resistance [27]. However, the higher the amount of fine sand replaced by expanded perlite, the greater the mass loss and the lower the freeze-thaw cycle resistance of foam concrete, which can be attributed to the higher porosity of expanded perlite than that of fine sand [28]. Moreover, under the same density, reducing aggregate content and increasing cement content was found to be beneficial to the freeze-thaw resistance of foam concrete [31].

Furthermore, the addition of fiber can considerably influence the freeze-thaw cycle resistance of foam concrete. It was reported [31] that the freeze-thaw cycle resistance of foam concrete increased with increased polypropylene fiber content. However, the addition of basalt fiber reduces the freeze-thaw cycle resistance of foam concrete, possibly due to the presence of fibrous materials reducing the integration of paste [32]. Tang et al. [33] indicated that foam concrete containing recycled polyester fiber possessed greater freeze-thaw cycle resistance than polyester fiber-containing foam concrete, while both had greater resistance to the freeze-thaw cycle than foam concrete without fiber.

Few studies exist on the freeze-thaw cycle resistance of GFC. Alzaza et al. [34] claimed that the higher the foam content in GFC, the lower the freeze-thaw cycle resistance, and that the ratio of stone wool to glass wool in the precursor had little effect on the freeze-thaw cycle resistance of GFC. According to Bumanis et al. [35], the freeze-thaw cycle resistance of

metakaolin-based GFC was superior to that of illite-based GFC, which may be related to the reactive SiO2/Al2O3 ratio and pore size distribution, demonstrating that the replacement of fine sand with dolomite powder has no significant effect on the freeze-thaw cycle resistance of GFC. The addition of fibers (such as polypropylene fibers) to GFC reduced the freeze-thaw cycle resistance of GFC [34]. In addition, little research has been undertaken on the freeze-thaw cycle resistance of MPC foam concrete, SAC foam concrete, and LC^3 foam concrete. In order to apply foam concrete made from these materials as a peripheral maintenance structure in freeze-thaw areas, further substantial exploration on freeze-thaw cycle resistance is necessary.

3. Elevated Temperature Resistance

After exposure to elevated temperature or fire, concrete will undergo a series of irreversible processes, such as loss of free and chemically bound water, phase transformation, cracking, spalling, and so on, leading to failure [36]. At 150 °C, most free water or physically bound water will evaporate [37]. When the temperature reaches 400 °C to 600 °C, the calcium hydroxide in the concrete will decompose and the water produced will become vapor and disappear. If the water vapor has insufficient escape channels, it will cause internal stress in the concrete, leading to cracking and spalling [38]. Foam concrete has acceptable elevated temperature resistance due to its porosity, making it generally superior to the elevated temperature resistance of ordinary concrete [39]. Nevertheless, the water in foam concrete undergoes high evaporation under elevated temperature, leading to the excessive shrinkage of foam concrete [40]. Lia et al. [41] concluded that foam concrete walls can provide more evacuation time under fire through numerical simulation. Elevated temperature can cause changes in the mechanical properties and stiffness of foam concrete, and even cracks. The compressive strength of foam concrete tends to increase during a temperature rise to 400 °C, as the chemical reaction of the binder is promoted by elevated temperature. Once the temperature has surpassed 400 °C, the compressive strength gradually decreases, due to the decomposition of calcium hydroxide and other substances [25,42,43]. In addition, regardless of the density of foam concrete, when the temperature reaches approximately 90 °C, foam concrete exhibits a loss of stiffness due to the generation of microcracks [44]. After the temperature reaches 400 °C, macroscopic cracks tend to appear on the surface of foam concrete. The higher the temperature of foam concrete, the greater the number of cracks, and the higher the density, the greater the number of cracks at the same temperature [45]. It is reported that foam concrete that cools slowly in air after exposure to elevated temperature is more likely to crack, resulting in a greater loss of strength than foam concrete that cools rapidly in water [25].

The density of foam concrete is an important factor affecting elevated temperature resistance. Figure 1 shows the relationship between OPC foam concrete density and fire duration. Generally, within a certain density range, the elevated temperature resistance of foam concrete increases proportionally as density decreases. It has been reported that foam concrete with a density of 950 kg/m^3 can withstand a fire of 3.5h, while foam concrete with a density of 1200 kg/m^3 can only withstand a fire of 2h [46]. Jones and McCarthy [47] conducted fire resistance tests on 100 mm-thick foam concrete slabs with densities of 930 kg/m^3 and 1250 kg/m^3, respectively, and the results showed that the former withstood fire for a longer duration and had superior elevated temperature resistance. However, the opposite occurs at lower densities. According to Vilches et al., the elevated temperature resistance of ultralight foam concrete with a density of 150 kg/m^3 was more than three times lower than that of ultralight foam concrete with a density of 400 kg/m^3 [48]. It was reported that density-related pore structures in foam concrete were only minimally affected by elevated temperature [44].
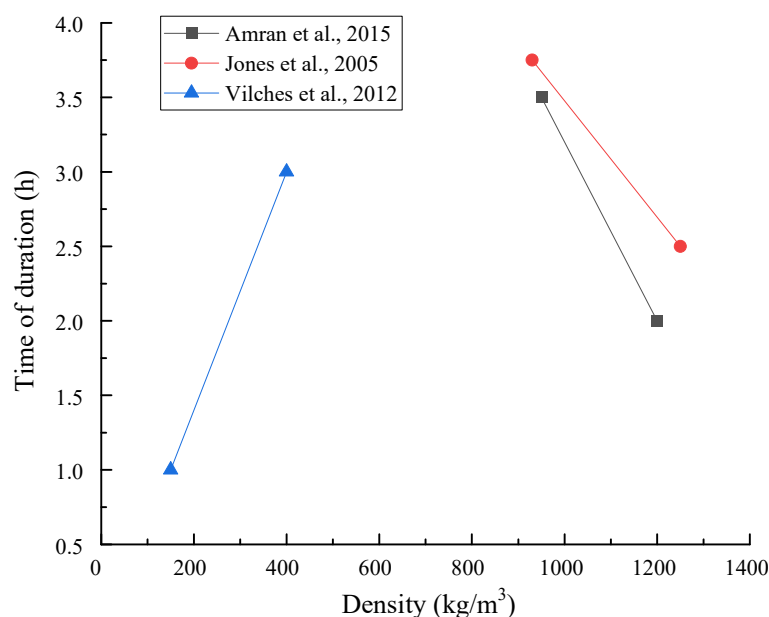
Figure 1. Relationship between OPC foam concrete density and fire duration [46–48].

In addition, the mix proportion and composition of foam concrete are important factors affecting elevated temperature resistance. Foam concrete produced using cement with an Al_2O_3/CaO ratio higher than 2 has been reported to show no signs of spalling or explosion at 1450 °C, whereas dense ordinary concrete does [49]. The addition of Pozzolanic additives can increase the strength of foam concrete with increased temperature within a certain temperature range and improve the elevated temperature resistance of foam concrete [20]. Foam concrete partially replacing cement with fly ash has a higher elevated temperature resistance than foam concrete without fly ash within the density range of 600–1400 kg/m^3 [50]. It was reported that the addition of rice husk ash resulted in the elevated temperature resistance of foam concrete at 200–800 °C surpassing that of foam concrete without rice husk ash, and that the high temperature resistance increased with increased rice husk ash addition within a certain range [25].

In terms of aggregates, ordinary concrete will produce significant partial differential shrinkage, expansion, and cracking at elevated temperature due to the presence of coarse aggregates, while foam concrete has substantial elevated temperature resistance because it contains only fine aggregate [51]. Gencel et al. improved the elevated temperature resistance of foam concrete by partially replacing fine sand with waste marble powder, with elevated temperature resistance increasing with increased replacement within a certain amount of replacement [25]. However, the use of expanded polystyrene particles as fine aggregates in foam concrete reduces elevated temperature resistance [52]. Additionally, it was reported [50] that polypropylene fiber melts at close to 160–170 °C, forming small channels for water vapor escape and reducing the internal vapor pressure of foam concrete at elevated temperature. Thus, increasing elevated temperature resistance and the addition of polypropylene fiber can reduce shrinkage cracks at elevated temperatures and thus reduce spalling.

In terms of GFC, its elevated temperature resistance is superior to that of geopolymer concrete due to its porous structure [53]. Changes in compressive strength and the elevated temperature resistance of GFC at elevated temperature are affected by the type, proportion, and quantity of precursors and activators. It was reported that the strength of fly ash-based GFC decreases at 100–400 °C, but when the temperature exceeds 400 °C, the unreacted fly ash will be sintered. This results in strength increase, depending on the Si/Al ratio in the binder—the higher the Si/Al ratio, the higher the strength increase [42,53–55]. The compressive strength of GFC in which the fly ash is partially replaced with slag gradually increased with temperature up to 100 °C, but decreased once the temperature exceeded

100 °C, indicating reduced elevated temperature resistance [42]. However, the compressive strength of GFC in which fly ash is partially replaced with slag gradually increased at temperatures up to 100 °C, and then declined once the temperature exceeded 100 °C, indicating reduced temperature resistance [42]. Furthermore, metakaolin-based GFC was said to enjoy excellent elevated temperature resistance [56–61]. Peng et al. exposed one side of a 20 mm-thick metakaolin-based GFC sample to a temperature of 1100 °C. After three hours, the measured temperature on the opposite side was lower than 250 °C and the pore structure did not collapse, indicating good elevated temperature resistance [62].

The addition of fibers can greatly improve the elevated temperature resistance of foam concrete [8]. It was reported that the addition of basalt fiber increased the compressive strength of GFC under elevated temperature, increasing more significantly with increases in the amount of addition [63,64]. The elevated temperature resistance of polyvinyl alcohol fiber-reinforced GFC increased with increasing fiber content when no more than 2% polyvinyl alcohol fiber was added. However, when the dosage exceeded 2%, its elevated temperature resistance reduced to below that of unadded GFC at temperatures above the melting point of polyvinyl alcohol fiber (200 °C), which was caused by excessive porosity generated by immoderate polyvinyl alcohol fiber melting [65]. In addition, Masi et al. [66] showed that the elevated temperature resistance of polyvinyl alcohol fiber-reinforced GFC was superior to that of basalt fiber-reinforced GFC. Polypropylene fiber with a low melting point (160–175 °C) can produce small channels in GFC for water vapor escape after melting, which reduces the internal vapor pressure of the GFC at elevated temperature and increases elevated temperature resistance [61]. According to the research of Li et al. [67], wollastonite fiber-reinforced metakaolin-based GFC offers high elevated temperature resistance.

Little research exists on the elevated temperature resistance of MPC foam concrete, SAC foam concrete, and LC^3 foam concrete. As an inorganic thermal insulation material, foam concrete enjoys excellent elevated temperature resistance and has broad future application potential. Nonetheless, the elevated temperature resistance of fast-setting, more stable, and more environmentally friendly foam concrete requires further exploration.

4. Carbonation Resistance

Concrete is carbonized when exposed to the atmosphere, which is a process by which cement hydration products, such as calcium hydroxide ($Ca(OH)_2$), calcium silicate hydrate (CSH), and calcium aluminate hydrate (CAH), chemically react with CO_2 to form calcium carbonate ($CaCO_3$) [68]. Since these reactions cause the pH of the porous solution of concrete to decrease, the destruction of the protective layer of oxide film on the surface of the rebar, and eventually the corrosion of the rebar, results. Loon et al. showed that OPC foam concrete has higher carbonation compared to normal concrete after one and a half years of carbonation testing [69]. Foam concrete was reported to have larger crystals after carbonation as well as more closed pores, due to the formation of modified silica gel and $CaCO_3$ [70]. The porosity and pore morphology of foam concrete are important factors affecting carbonation resistance. Loon et al. [69] and Jones et al. [47] both reported the higher porosity (the lower the density, the higher the carbonation rate) of foam concrete, with the presence of more open pores resulting in a higher carbonation rate [7].

In addition, the mix proportion and composition of foam concrete are important factors affecting carbonation resistance. It has been reported that the higher the water-cement ratio, the lower the carbonation resistance of foam concrete due to the greater formation of capillaries [71]. Foam concrete with fly ash partially replacing cement has higher carbonation resistance as the volcanic reaction of fly ash improves the pore structure, but foam concrete with fly ash partially replacing cement has lower carbonation resistance when the water-binder ratio is relatively high [72]. Tian et al. stated that, in foam concrete containing phosphogypsum, concrete with the partial replacement of cement with ground granulated blast furnace slag has superior carbonation resistance to foam concrete with a partial replacement of cement with fly ash [73]. Park and Choi investigated the carbonation resistance of foam concrete partially replacing cement with stainless steel-argon oxygen

decarburization slag, wherein the results showed that the addition of stainless steel-argon oxygen decarburization slag promoted carbonation [72]. Brady et al. [74] and Jones et al. [75] reported similar results, finding that foam concrete using FA as a fine aggregate offered higher carbonation resistance at lower densities and lower carbonation resistance at higher densities than fine sand foam concrete. The application of integral and non-integral surface treatment agents proved an effective method by which to delay the carbonation rate of foam concrete [76].

GFC exhibits better carbonation resistance due to its chemical composition [8]. Carbonation of the GFC forms sodium carbonate (Na_2CO_3) and $CaCO_3$ crystals, which further leads to an increase in strength and density [77]. Porosity and pore morphology significantly affect the carbonation resistance of GFC. GFC with higher porosity exhibits a higher carbonation rate because the volume of gas penetrating the GFC is directly related to porosity [34]. Further, more open pores result in higher carbonation rates [78]. GFC with different precursors and activators has different carbonation responses. Mastali et al. [77] reported that ground granulated blast furnace slag-based GFC increased density and compressive strength by up to 6% and 30%, respectively, under carbonation. Alzaza et al. also concluded that density and compressive strength increase after carbonation [34]. In terms of SAC foam concrete, the smaller the pore size and the higher the pore integrity, the better the carbonation resistance of foam concrete, with SAC foam concrete exhibiting greater carbonation resistance after waterproofing treatment [79]. Singh and Scrivener reported that LC^3 foam concrete accelerated carbonation when autoclaved [80].

It is worth mentioning that the carbonation resistance and effects of the carbonation of waste recycling foam concrete, GFC, SAC foam concrete, MPC foam concrete, and LC^3 foam concrete have not been widely studied, despite their substantial impact on the life of foam concrete members.

5. Efflorescence Resistance

When concrete comes into contact with water or is exposed to moist air, it can produce efflorescence—the development of white salt deposits on its surface. Although the efflorescence of ordinary concrete can cause a change in color on the concrete surface, it is nevertheless harmless and the degree of efflorescence tends to be low [81]. However, the efflorescence of geopolymer is a serious problem because geopolymer has a large number of soluble alkalis, in which alkaline cations dissolve in water and leach to the surface with water through pores, where they react with atmospheric CO_2 to form white carbonate surface sediments [82,83]. Little research is available on the efflorescence of OPC foam concrete because the low soluble alkali content of OPC foam concrete makes its degree of efflorescence much lower, which has little effect on the performance of OPC foam concrete [84]. For GFC, the larger pore size and higher porosity of GFC lead to more severe efflorescence, potentially causing surface wear or even spalling [81,85].

It has been reported that fly ash-based GFC has high porosity and a large pore size, allowing the soluble alkali to leak rapidly and resulting in the rapid efflorescence of GFC [86]. Alzaza et al. investigated the efflorescence properties of polypropylene fiber-reinforced stone wool and metakaolin blends-based GFC, and the results showed that, after the seven-day efflorescence test, the higher stone wool content and the addition of polypropylene fiber led to more severe efflorescence, and the higher porosity resulted in more severe efflorescence due to higher water penetration and the release of alkali cations [34]. Nevertheless, Şahin et al. showed that slag-based GFC with higher porosity exhibited lower efflorescence due to its lower solids content, resulting in a reduced quantity of leachable alkali solution [87]. If GFC is to be applied to peripheral members exposed to moisture, its efflorescence problem must be solved. The applicability and effectiveness of current methods applied to enhancing efflorescence resistance in solid geopolymer concrete—such as reducing the number of leachable alkali cations by applying heat curing or using active precursors to increase the degree of reaction—and reducing water intrusion into concrete by increasing the hydrophobicity of the concrete surface [88,89] have yet to be

further tested in GFC [83]. In addition, the current studies do not cover the efflorescence properties and efflorescence resistance of SAC foam concrete, MPC foam concrete, and LC^3 foam concrete, which hinders the widespread application of these foam concretes in humid environments.

6. Resistance to Aggressive Environments

Aggressive environments, such as those involving acid, sulfate, chloride, and so on, can affect the service performance of foam concrete quite considerably. Porosity, pore size, pore distribution, pore morphology, and the mixture composition of foam concrete determine the extent to which foam concrete is affected in the erosion environment [46].

6.1. Resistance to Acid Environment

Acid is one of the aggressive agents that affect the service performance of foam concrete. It was reported that, on exposure to a solution of 5% hydrochloric acid, the mass loss of OPC foam concrete increased with decreased density, due to increased porosity leading to an increase in the acid-exposed contact area and acid diffusion rate. The mass loss decreased with increasing basalt fiber content, due to the higher acid erosion resistance of basalt fiber [90]. Rokiah et al. claimed that foam concrete in which 30% of its weight was replaced with processed spent bleaching earth experienced a lower mass loss in pH 2 hydrochloric acid solution than pure OPC foam concrete, indicating enhanced acid erosion resistance. This arises since processed spent bleaching earth can undergo a pozzolanic reaction with calcium hydroxide, reducing the amount of calcium hydroxide susceptible to acid erosion [91]. The addition of fly ash can also enhance the resistance of foam concrete to acid erosion [92]. According to Li et al. [93], under 5% diluted hydrochloric acid erosion, the mass loss and strength loss of phosphogypsum-based foam concrete are lower than those of OPC foam concrete, because OPC foam concrete has more cement that is easily eroded by acid. In addition, under the erosion of sulfuric acid at a concentration of 3%, the mass increase of OPC foam concrete decreases with increased density, and the mass increase of foam concrete replacing 20% cement with silica fume is lower than that of pure OPC foam concrete after 56 days of immersion [27].

Interestingly, another study by Bayraktar et al. showed that, under the erosion of a 5% sulfuric acid solution, foam concrete without basalt fiber first experienced mass loss and eventually mass increase, while mixtures containing basalt fiber experienced only mass loss. The mass loss increased with increased basalt fiber content and increased with decreased foam concrete density [90]. Whether OPC foam concrete experiences mass loss or mass increase in sulfuric acid solution depends on the relative magnitude of the dissolution rate of cement hydration products and the formation rate of ettringite. Madhwani et al. [94] studied the effect of sulfuric acid attack on the compressive strength of sugarcane bagasse fiber-reinforced foam concrete and demonstrated a compressive strength reduction rate of up to 25%. The partial replacement of cement with silica ash and waste marble powder greatly reduces the mass loss and strength loss of foam concrete under the erosion of 5% sulfuric acid solution, mainly due to the pozzolanic reaction densifying the microstructure and reducing the calcium hydroxide content [95]. Good resistance to fly ash-slag blends-based GFC in acidic environments has also been reported [96]. In addition, the type of alkaline element in the activator affects the deterioration mechanism of GFC in an acidic environment.

As for GFC, the dissolution of geopolymer gel and leaching of alkali cations are two mechanisms of the deterioration of GFC under acid attack. It was reported that fly ash-based GFC exposed to hydrochloric or sulfuric acid for long periods (90, 180, and 360 days) at room temperature exhibited a decrease in compressive strength, a decrease in Young's modulus, and a loss of mass, caused by the simultaneous dissolution of N-A-S-H gel and the leaching of aluminum ions. Furthermore, it was pointed out that the C-S-H gel in OPC foam concrete was more soluble in the acid environment than the N-A-S-H gel in GFC, resulting in the greater resistance of GFC [55]. The deterioration mechanism of

metakaolin-based GFC using sodium silicate and sodium hydroxide as activators showed only the leaching of alkaline cations, whereas the deterioration mechanism of GFC using potassium silicate and potassium hydroxide as activators was manifested by the combined effect of the dissolution of geopolymer gel and leaching of alkali cations [97]. According to the report [98], the use of a precursor with low calcium content increases the resistance of GFC to acid attack.

6.2. Resistance to Sulfate Environment

Sulfate is one of the aggressive agents that can shorten the service life of foam concrete. Sulfate erosion is a complex mechanism that depends on many variables, including density, water-cement ratio, presence of mineral admixtures, cation type associated with sulfate anions, sulfate concentration, exposure time, and cement type [99]. OPC foam concrete has good expansion resistance under sulfate erosion [100] and a lower expansion and extent of deterioration compared to normal concrete [101]. Density is an important factor affecting the properties of foam concrete under sulfate attack. In the high-density range, the expansion rate of OPC foam concrete in the sulfate environment increases with decreased density. This is because decreased density leads to increased porosity, resulting in an increase in sulfate diffusion rate [31,90]. In the medium-density and low-density ranges, the expansion rate of OPC foam concrete decreases with decreasing density due to sufficient internal pore space to accommodate the products of sulfate erosion [102]. Mamun and Bindiganavile reported that exposure to sodium sulfate had a more significant effect on the flexural strength of foam concrete than on the compressive strength of foam concrete, and that higher density foam concrete decreased more significantly in strength under sodium sulfate erosion due to its greater susceptibility to expansion caused by ettringite formation [103]. Interestingly, in the density range of 300–420 kg/m^3, the compressive strength of foam concrete after exposure to a sulfate environment increases with the increase of dry density, and the compressive strength at a dry density of 420 kg/m^3 is higher than that of unexposed foam concrete because the reaction products promote the formation of closed pores. Liu et al. mentioned that the smaller the water-cement ratio, the better the sulfate resistance of foam concrete [104]. Mineral admixtures, such as fly ash, silica fume, and fine-grained ground granulated blast-furnace slag, as cement replacements in appropriate proportions, can improve sulfate resistance in foam concrete [92,105], as shown in Table 2.

Table 2. The effects of various mineral admixtures on the sulfate resistance of OPC foam concrete.

Type of Materials	Variation in Sulfate Resistance	Reference
Fly ash	Increase	[92]
Ground granulated blast furnace slag	Increase	[105]
Silica fume	Increase	[95]
Waste marble powder	Increase	[95]
Rubber powder	Decrease	[104]
Processed spent bleaching earth	Increase	[106]

Zhang et al. studied the performance of foam concrete soaked in 10% magnesium sulfate solution for 153 days. The results showed that the partial replacement of cement with silica fume and waste marble powder reduced the strength loss of foam concrete, indicating superior sulfate resistance, which is due to the pozzolanic reaction reducing the calcium hydroxide content and the chemical filling of silica fume, as well as the physical filling of waste marble powder to form a dense microstructure, preventing the entry of sulfate ions and thus inhibiting the formation of gypsum and ettringite [95]. Liu et al. studied the effect of rubber powder on the sulfate resistance of foam concrete and showed that the sulfate resistance of foam concrete decreased rapidly when the amount of rubber powder added exceeded 0.11% of the cement weight [104]. Rokiah et al. replaced 30%

cement with processed spent bleaching earth to make the internal structure of foam concrete denser and improve sulfate resistance [106].

The use of fly ash as an alternative to fine sand can also improve the sulfate resistance of foam concrete [100]. The addition of polypropylene fibers has been reported to increase the porosity of foam concrete, leading to increased expansion and reduced sulfate resistance [31]. Furthermore, the type of cation associated with sulfate anions is a significant factor affecting the post-exposure performance of foam concrete. The expansion value of foam concrete exposed to a sodium sulfate environment is 28% higher than that of foam concrete exposed to a magnesium sulfate environment, mainly due to ettringite more easily forming in the sodium sulfate environment. Meanwhile, the disintegration and softening of cementing material in the high-quality fraction magnesium sulfate environment is the main source of the deterioration of foam concrete, in which magnesium sulfate reacts with cementitious C-S-H gel to form non-cementitious M-S-H and reacts with calcium hydroxide to form gypsum, resulting in softening of the cementitious structure and making the surface of foam concrete more prone to spalling.

Further, sulfate concentration significantly influences the performance of foam concrete after exposure. The expansion rate of foam concrete exposed to a high concentration of sodium sulfate or magnesium sulfate is much higher than that of foam concrete exposed to a low concentration of sodium sulfate or magnesium sulfate. It was found that the expansion rate continued to increase with prolonged exposure [101]. It is worth mentioning that the thermal conductivity of foam concrete showed an upward trend during the first few days of exposure to a sodium sulfate environment, while the thermal conductivity gradually returned to its original value and remained largely unchanged over a longer exposure period [107].

Few studies have been conducted on the resistance of GFC in a sulfate environment. Top et al. claimed that GFC formed using a low calcium precursor is more resistant to sulfate attack than OPC foam concrete due to lower calcium hydroxide content [98]. It was reported that the compressive strength of GFC decreased more significantly in magnesium sulfate than in sodium sulfate [55]. In addition, Li et al. [93] found that, under 5% sodium sulfate attack, the mass increase of phosphogypsum-based foam concrete was lower than that of OPC foam concrete and had increased resistance to sulfate erosion. This is because phosphogypsum-based foam concrete contained less calcium hydroxide and calcium aluminate hydrate to react with SO_4^{2-}.

6.3. Resistance to Chloride Environment

The application of foam concrete in structures and semi-structures inevitably requires the configuration of steel bars. The intrusion of chloride in rebar-reinforced foam concrete can cause corrosion of the rebar and reduce service life. Chloride that penetrates the surface of the rebar destroys the passivation layer on the surface of the rebar by continuously reducing the pH value around the rebar through a chemical reaction. When the chloride concentration reaches a critical concentration, the local corrosion (pitting) of the steel bar begins, potentially causing more serious consequences than the uniform corrosion of the steel bar caused by carbonization [76]. Since the pores in foam concrete are not continuous, they can prevent rapid penetration and play a buffering role, giving OPC foam concrete a certain resistance to chloride penetration into the steel bar, which is comparable to normal concrete [108,109].

It was reported that the chloride penetration rate for OPC foam concrete increased with increased foam content, and the higher the water-cement ratio, the higher the chloride penetration rate [110,111]. The partial replacement of cement with supplementary cementitious materials such as fly ash or ground granulated blast-furnace slag can greatly reduce the penetration rate of chloride in foam concrete [92,112]. However, Rooyen observed that the addition of fly ash to foam concrete resulted in an increase in chloride penetration depth, because reduced pore size led to higher capillary suction [76]. Wasim et al. [113] conducted an 803-day chloride erosion test to study the effect of different concentrations of

chloride solution on the corrosion rate of steel bars in foam concrete, the results of which showed that the corrosion rate following immersion in 5% chloride solution was higher than that following immersion in 3% chloride solution. An effective way to prevent the penetration of aggressive agents is to use surface treatment agents such as hydrophobic agents, pore-blockers, and so on, on the surface of foam concrete, which can effectively reduce the penetration rate and depth of chloride [76,114]. However, high cost and complexity limit its application [115].

In terms of GFC, the compressive strength and Young's modulus of fly ash-based GFC immersed in sodium chloride solution are significantly reduced, but the mass remains largely unchanged [55]. Wasim et al. studied the effect of different concentrations of chloride solution on the corrosion rate of steel bars in GFC and showed that the corrosion rate of steel bars increased with increased chloride concentration. Furthermore, under the same concentration of chloride solution erosion, the corrosion rate of GFC in high-temperature and high-humidity environments is much higher than that of GFC in lower temperature and humidity environments [116].

The resistance of SAC foam concrete, MPC foam concrete, and LC^3 foam concrete to aggressive environments has not yet been studied extensively, despite its important influence on the performance and longevity of these three foam concrete members. The application of these three types of foam concrete in aggressive environments, such as the offshore environment, marine environment, and so on, and in reinforced structures, requires significantly more research.

7. Resistance to Alkali-Silica Reaction

The alkali-silica reaction refers to the reaction of alkali in cement with silica under wet conditions after concrete is hardened. A considerable alkali-silica reaction will cause the internal expansion of the concrete, resulting in its widespread cracking and deterioration. In lower density foam concrete, the alkali-silica reaction is not a problem, while in higher density foam concrete, a substantial alkali-silica reaction may cause foam concrete to expand and crack [117]. It has been reported that the alkali-silica reaction expansion rate of foam concrete is much lower than that of normal concrete with the same mix proportion, due to the presence of the large number of pores in foam concrete [118]. Furthermore, the application of low-lime class f fly ash can significantly reduce the expansion caused by the alkali-silica reaction in foam concrete due to the consumption of a large amount of alkali by the pozzolanic reaction [93].

Kumar and Chinnaraju tested the expansion rate of a variety of foam concretes in sodium hydroxide solution for 28 days and 365 days, and the results showed that the alkali-silica reaction expansion rate of foam concrete in which cement is partially replaced with glass powder increased with increased glass powder content, while the addition of nano bio-carbonate reduced the alkali-silica reaction expansion rate [118]. Massekh studied the alkali-silica reaction characteristics of foam concrete in which the sand is partially replaced with waste glass immersed in the sodium hydroxide solution and showed that the expansion rate caused by the alkali-silica reaction increased with the increased replacement amount of waste glass and was greater than the expansion rate of the foam concrete without waste glass. Additionally, the chemical composition and particle size of the waste glass greatly affected the alkali-silica reaction expansion of foam concrete. Some studies also showed that the introduction of polypropylene fibers could reduce the expansion of the alkali-silica reaction [118,119]. Gencel et al. partially replaced the expanded perlite with fine glass sand in foam concrete, reducing the expansion of the alkali-silica reaction, which was caused by the dispersion of the alkali enhanced by fine glass sand [28].

It should be mentioned that the use of fewer aggregates in GFC and the presence of a greater number of pores reduce the severity of the alkali-silica reaction, such that the alkali-silica reaction of GFC has not been widely studied. Additionally, commonly used SAC foam concrete and MPC foam concrete generally do not involve alkali-silica reaction

problems. More research is needed on the alkali-silica reaction of LC^3 foam concrete to explore the effect of the alkali-silica reaction.

8. Conclusions and Future Work

In this review, durability characteristics such as freeze-thaw cycle resistance, elevated temperature resistance, carbonation resistance, efflorescence resistance, acid resistance, sulfate resistance, chloride resistance, and alkali-silica reaction are mentioned in relation to OPC foam concrete, GFC, SAC foam concrete, MPC foam concrete, and LC^3 foam concrete. Foam concrete has good freeze-thaw cycle resistance, elevated temperature resistance, and expansion resistance caused by sulfate erosion and alkali-silica reaction, while having poor carbonation resistance, efflorescence resistance, acid resistance, and chloride resistance. Improving the durability of foam concrete is extremely important to increase the service life of foam concrete members and reinforced members. At present, research on the durability of foam concrete is quite limited, especially around SAC foam concrete, MPC foam concrete, and LC^3 foam concrete, which hinders the wide application of foam concrete in practice. Based on the review of durability, the following ideas and future work are proposed:

- The effects of CO_2 curing on the freeze-thaw cycle resistance of foam concrete and the effect of fiber addition on the freeze-thaw cycle resistance and elevated temperature resistance of foam concrete require further investigation.
- The elevated temperature resistance of foam concrete and ordinary concrete with the same strength is worth exploring, which will contribute to the application of foam concrete in structures.
- The elevated temperature resistance of foam concrete with supplementary cementitious materials such as ground granulated blast-furnace slag, silica fume, and so on, and various wastes as cement replacements should be evaluated. The elevated temperature resistance of high-density structural foam concrete also requires further research. In addition, the elevated temperature resistance of fast-setting foam concrete with more stable foam needs to be further explored.
- Foam concrete that uses waste to partially replace cement can greatly reduce the carbon footprint, but its carbonation resistance has not been studied, which is a direction worth exploring. Furthermore, the effect of the addition of fibers on the carbonization of foam concrete is unknown.
- Efflorescence has a considerable effect on GFC, but few studies have been conducted. Methods by which to reduce GFC efflorescence remain to be studied, such as reducing the size of pores by delayed pozzolanic reaction, using surface water-repellent coatings or water-repellent agents to prevent moisture ingress, and so on.
- The effect of fiber addition on the erosion environment resistance of foam concrete must be further investigated. In addition, the influence of the erosion environment on the performance of foam concrete members reinforced with FRP bars remains unexplored.
- Using the correct amount of low calcium oxide fly ash, silica fume, and other materials that can produce delayed pozzolanic reactions is an effective method by which to increase the resistance of foam concrete to an aggressive environment, due to the lower calcium hydroxide content and more closed pore system. Furthermore, it is speculated that the addition of an appropriate amount of limestone can reduce the expansion caused by sulfate erosion.
- Research on the durability of SAC foam concrete, MPC foam concrete, and LC^3 foam concrete is vastly insufficient. In addition, the effects of initial foam size, gas type in foam, and curing conditions on the durability of foam concrete are worth exploring.
- Increasing the number of closed pores, reducing the connectivity of pores, reducing the number of surface pores, distributing the pores more uniformly and regularizing the pore morphology are effective ways by which to increase the durability of foam concrete.

References

1. Alexander, M.; Bentur, A.; Mindess, S. *Durability of Concrete: Design and Construction*; CRC Press: Boca Raton, FL, USA, 2017; Volume 20.
2. Tang, S.W.; Yao, Y.; Andrade, C.; Li, Z. Recent durability studies on concrete structure. *Cem. Concr. Res.* **2015**, *78*, 143–154. [CrossRef]
3. Li, Z.; Zhou, X.; Ma, H.; Hou, D. *Advanced Concrete Technology*; John Wiley & Sons: Hoboken, NJ, USA, 2022.
4. DuraCrete. *Probabilistic Performance Based Durability Design of Concrete Structures: The European Union–Brite EuRam III Final Technical Report of Duracrete Project*; Document BE95-1347/R17; CUR: Gouda, The Netherlands, 2000.
5. Rybakov, V.; Kozinetc, K.; Vatin, N.; Velichkin, V.; Korsun, V. Lightweight steel concrete structures technology with foam fiber-cement sheets. *Mag. Civ. Eng.* **2018**, *6*, 103–111.
6. Kudyakov, A.I.; Steshenko, A.B. Heat insulating reinforced air hardened foamed concrete. *Vestn. Tomsk. State Univ. Archit. Build. Engl. Version Append.* **2014**, *1*, 60–65.
7. Raj, A.; Sathyan, D.; Mini, K. Physical and functional characteristics of foam concrete: A review. *Constr. Build. Mater.* **2019**, *221*, 787–799. [CrossRef]
8. Kočí, V.; Černý, R. Directly foamed geopolymers: A review of recent studies. *Cem. Concr. Compos.* **2022**, *130*, 104530. [CrossRef]
9. Bindiganavile, V.; Hoseini, M. Foamed concrete. In *Developments in the Formulation and Reinforcement of Concrete*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 365–390.
10. Senbu, O.; Kamada, E. Mechanism and evaluation method of frost deterioration of cellular concrete, durability of building materials and components. In Proceedings of the 5th International Conference on the Durability of Building Materials and Components, Brighton, UK, 7–9 November 1990; pp. 241–246.
11. Li, T.; Wang, Z.; Zhou, T.; He, Y.; Huang, F. Preparation and properties of magnesium phosphate cement foam concrete with H_2O_2 as foaming agent. *Constr. Build. Mater.* **2019**, *205*, 566–573. [CrossRef]
12. Aroni, S. *Autoclaved Aerated Concrete-Properties, Testing and Design*; CRC Press: Boca Raton, FL, USA, 2004.
13. Roulet, C. Expansion of aerated concrete due to frost: Determination of critical saturation. In *Proceedings Autoclaved Aerated Concrete, Moisture and Properties*; Elsevier: Amsterdam, The Netherlands, 1983; pp. 157–169.
14. Kamada, E.; Koh, Y.; Tapata, M. Frost deterioration of cellular concrete. In Proceedings of the 3rd International Conference on the Durability of Building Materials and Components, Espoo, Finland, 12–15 August 1984; pp. 372–382.
15. Allen, R.; Baldini, N.; Donofrio, P.; Gutman, E.; Keefe, E.; Kramer, J.; Leinweber, C.; Mayer, V. *Annual Book of ASTM Standards*; ASTM: West Conshohocken, PA, USA, 1998; p. 188.
16. Tikalsky, P.J.; Pospisil, J.; MacDonald, W. A method for assessment of the freeze–thaw resistance of preformed foam cellular concrete. *Cem. Concr. Res.* **2004**, *34*, 889–893. [CrossRef]
17. Brewer, W. Controlled low strength materials (CLSM), radical concrete technology. In Proceedings of the International Conference on Concrete in the Service of Mankind, Dundee, UK, 24–26 June 1996; pp. 27–28.
18. Shon, C.-S.; Lee, D.; Kim, J.-H.; Chung, C.-W. Freezing and thawing resistance of cellular concrete containing binary and ternary cementitious mixtures. *Constr. Build. Mater.* **2018**, *168*, 73–81. [CrossRef]
19. She, W.; Du, Y.; Zhao, G.; Feng, P.; Zhang, Y.; Cao, X. Influence of coarse fly ash on the performance of foam concrete and its application in high-speed railway roadbeds. *Constr. Build. Mater.* **2018**, *170*, 153–166. [CrossRef]
20. Gencel, O.; Bilir, T.; Bademler, Z.; Ozbakkaloglu, T. A detailed review on foam concrete composites: Ingredients, properties, and microstructure. *Appl. Sci.* **2022**, *12*, 5752. [CrossRef]
21. Zhang, S.; Qi, X.; Guo, S.; Zhang, L.; Ren, J. A systematic research on foamed concrete: The effects of foam content, fly ash, slag, silica fume and water-to-binder ratio. *Constr. Build. Mater.* **2022**, *339*, 127683. [CrossRef]
22. Bayraktar, O.Y.; Kaplan, G.; Gencel, O.; Benli, A.; Sutcu, M. Physico-mechanical, durability and thermal properties of basalt fiber reinforced foamed concrete containing waste marble powder and slag. *Constr. Build. Mater.* **2021**, *288*, 123128. [CrossRef]
23. Gong, J.; Zhang, W. The effects of pozzolanic powder on foam concrete pore structure and frost resistance. *Constr. Build. Mater.* **2019**, *208*, 135–143. [CrossRef]
24. Yuan, H.; Ge, Z.; Sun, R.; Xu, X.; Lu, Y.; Ling, Y.; Zhang, H. Drying shrinkage, durability and microstructure of foamed concrete containing high volume lime mud-fly ash. *Constr. Build. Mater.* **2022**, *327*, 126990. [CrossRef]

25. Gencel, O.; Benli, A.; Bayraktar, O.Y.; Kaplan, G.; Sutcu, M.; Elabade, W.A.T. Effect of waste marble powder and rice husk ash on the microstructural, physico-mechanical and transport properties of foam concretes exposed to high temperatures and freeze–thaw cycles. *Constr. Build. Mater.* **2021**, *291*, 123374. [CrossRef]

26. Wu, J.; Lv, C.; Pi, R.; Zhang, H.; Bi, Y.; Song, X.; Wang, Z. The stability and durability of silt-based foamed concrete: A new type of road engineering material. *Constr. Build. Mater.* **2021**, *304*, 124674. [CrossRef]

27. Bayraktar, O.Y.; Soylemez, H.; Kaplan, G.; Benli, A.; Gencel, O.; Turkoglu, M. Effect of cement dosage and waste tire rubber on the mechanical, transport and abrasion characteristics of foam concretes subjected to H2SO4 and freeze–thaw. *Constr. Build. Mater.* **2021**, *302*, 124229. [CrossRef]

28. Gencel, O.; Bayraktar, O.Y.; Kaplan, G.; Arslan, O.; Nodehi, M.; Benli, A.; Gholampour, A.; Ozbakkaloglu, T. Lightweight foam concrete containing expanded perlite and glass sand: Physico-mechanical, durability, and insulation properties. *Constr. Build. Mater.* **2022**, *320*, 126187. [CrossRef]

29. Hilal, A.A.; Thom, N.H.; Dawson, A.R. On void structure and strength of foamed concrete made without/with additives. *Constr. Build. Mater.* **2015**, *85*, 157–164. [CrossRef]

30. Hilal, A.A.; Thom, N.; Dawson, A. The use of additives to enhance properties of pre-formed foamed concrete. *Int. J. Eng. Technol.* **2015**, *7*, 286–293. [CrossRef]

31. Gencel, O.; Kazmi, S.M.S.; Munir, M.J.; Kaplan, G.; Bayraktar, O.Y.; Yarar, D.O.; Karimipour, A.; Ahmad, M.R. Influence of bottom ash and polypropylene fibers on the physico-mechanical, durability and thermal performance of foam concrete: An experimental investigation. *Constr. Build. Mater.* **2021**, *306*, 124887. [CrossRef]

32. Gencel, O.; Nodehi, M.; Bayraktar, O.Y.; Kaplan, G.; Benli, A.; Gholampour, A.; Ozbakkaloglu, T. Basalt fiber-reinforced foam concrete containing silica fume: An experimental study. *Constr. Build. Mater.* **2022**, *326*, 126861. [CrossRef]

33. Tang, R.; Wei, Q.; Zhang, K.; Jiang, S.; Shen, Z.; Zhang, Y.; Chow, C.W. Preparation and performance analysis of recycled PET fiber reinforced recycled foamed concrete. *J. Build. Eng.* **2022**, *57*, 104948. [CrossRef]

34. Alzaza, A.; Mastali, M.; Kinnunen, P.; Korat, L.; Abdollahnejad, Z.; Ducman, V.; Illikainen, M. Production of lightweight alkali activated mortars using mineral wools. *Materials* **2019**, *12*, 1695. [CrossRef] [PubMed]

35. Bumanis, G.; Vitola, L.; Bajare, D.; Dembovska, L.; Pundiene, I. Impact of reactive SiO2/Al2O3 ratio in precursor on durability of porous alkali activated materials. *Ceram. Int.* **2017**, *43*, 5471–5477. [CrossRef]

36. Morsy, M.; Rashad, A.M.; Shoukry, H.; Mokhtar, M. Potential use of limestone in metakaolin-based geopolymer activated with H_3PO_4 for thermal insulation. *Constr. Build. Mater.* **2019**, *229*, 117088. [CrossRef]

37. Abdel Hamid, E.; Abadir, M.; El-Razik, A.; El Naggar, K.; Shoukry, H. Performance assessment of fired bricks incorporating pomegranate peels waste. *Innov. Infrastruct. Solut.* **2023**, *8*, 18. [CrossRef]

38. Alghamdi, H.; Shoukry, H.; Abadel, A.A.; Khawaji, M. Performance assessment of limestone calcined clay cement (LC3)-Based lightweight green mortars incorporating recycled waste aggregate. *J. Mater. Res. Technol.* **2023**, *23*, 2065–2074. [CrossRef]

39. Shang, X.; Qu, N.; Li, J. Development and functional characteristics of novel foam concrete. *Constr. Build. Mater.* **2022**, *324*, 126666. [CrossRef]

40. Sach, J.; Sefert, H. Foamed concrete technology: Possibilities for thermal insulation at high temperatures. *CFI* **1999**, *76*, 23–30.

41. Li, Q.; Wang, H.; Zhang, Z.; Reid, A. Numerical simulation of porosity on thermal properties and fire resistance of foamed concrete. *J. Sustain. Cem. Based Mater.* **2013**, *2*, 13–19. [CrossRef]

42. Zhang, Z.; Provis, J.L.; Reid, A.; Wang, H. Mechanical, thermal insulation, thermal resistance and acoustic absorption properties of geopolymer foam concrete. *Cem. Concr. Compos.* **2015**, *62*, 97–105. [CrossRef]

43. Shi, J.; Liu, B.; He, Z.; Liu, Y.; Jiang, J.; Xiong, T.; Shi, J. A green ultra-lightweight chemically foamed concrete for building exterior: A feasibility study. *J. Clean. Prod.* **2021**, *288*, 125085. [CrossRef]

44. Mydin, M.A.O.; Wang, Y. Mechanical properties of foamed concrete exposed to high temperatures. *Constr. Build. Mater.* **2012**, *26*, 638–654. [CrossRef]

45. Tan, X.; Chen, W.; Wang, J.; Yang, D.; Qi, X.; Ma, Y.; Wang, X.; Ma, S.; Li, C. Influence of high temperature on the residual physical and mechanical properties of foamed concrete. *Constr. Build. Mater.* **2017**, *135*, 203–211. [CrossRef]

46. Amran, Y.M.; Farzadnia, N.; Ali, A.A. Properties and applications of foamed concrete; a review. *Constr. Build. Mater.* **2015**, *101*, 990–1005. [CrossRef]

47. Jones, M.; McCarthy, A. Preliminary views on the potential of foamed concrete as a structural material. *Mag. Concr. Res.* **2005**, *57*, 21–31. [CrossRef]

48. Vilches, J.; Ramezani, M.; Neitzert, T. Experimental investigation of the fire resistance of ultra lightweight foam concrete. *Int. J. Adv. Eng. Appl.* **2012**, *1*, 15–22.

49. Kearsley, E.; Mostert, H. The use of foamed concrete in refractories. In Proceedings of the International Conference on the Use of Foamed Concrete in Construction, Dundee, UK, 5 July 2005; pp. 89–96.

50. Soleimanzadeh, S.; Othuman, M.M. Influence of high temperatures on flexural strength of foamed concrete containing fly ash and polypropylene fiber. *Int. J. Eng. Trans. B Appl.* **2013**, *26*, 117–126. [CrossRef]

51. Leitch, F. The properties of aerated concrete in service. In Proceedings of the 2nd International Conference on Lightweight Concretes, London, UK, 14–15 April 1980; p. 329.

52. Sayadi, A.A.; Tapia, J.V.; Neitzert, T.R.; Clifton, G.C. Effects of expanded polystyrene (EPS) particles on fire resistance, thermal conductivity and compressive strength of foamed concrete. *Constr. Build. Mater.* **2016**, *112*, 716–724. [CrossRef]

53. Cheng-Yong, H.; Yun-Ming, L.; Abdullah, M.M.A.B.; Hussin, K. Thermal resistance variations of fly ash geopolymers: Foaming responses. *Sci. Rep.* **2017**, *7*, 45355. [CrossRef]

54. František, Š.; Rostislav, Š.; Zdeněk, T.; Petr, S.; Vít, Š.; Zuzana, Z. Preparation and properties of fly ashbased geopolymer foams. *Ceram. Silikáty* **2014**, *58*, 188–197.

55. Hlaváček, P.; Šmilauer, V.; Škvára, F.; Kopecký, L.; Šulc, R. Inorganic foams made from alkali-activated fly ash: Mechanical, chemical and physical properties. *J. Eur. Ceram. Soc.* **2015**, *35*, 703–709. [CrossRef]

56. Bai, C.; Conte, A.; Colombo, P. Open-cell phosphate-based geopolymer foams by frothing. *Mater. Lett.* **2017**, *188*, 379–382. [CrossRef]

57. Cilla, M.S.; de Mello Innocentini, M.D.; Morelli, M.R.; Colombo, P. Geopolymer foams obtained by the saponification/peroxide/gelcasting combined route using different soap foam precursors. *J. Am. Ceram. Soc.* **2017**, *100*, 3440–3450. [CrossRef]

58. Bai, C.; Franchin, G.; Elsayed, H.; Zaggia, A.; Conte, L.; Li, H.; Colombo, P. High-porosity geopolymer foams with tailored porosity for thermal insulation and wastewater treatment. *J. Mater. Res.* **2017**, *32*, 3251–3259. [CrossRef]

59. Bai, C.; Colombo, P. High-porosity geopolymer membrane supports by peroxide route with the addition of egg white as surfactant. *Ceram. Int.* **2017**, *43*, 2267–2273. [CrossRef]

60. Bai, C.; Zheng, J.; Rizzi, G.A.; Colombo, P. Low-temperature fabrication of SiC/geopolymer cellular composites. *Compos. Part B Eng.* **2018**, *137*, 23–30. [CrossRef]

61. Rickard, W.D.; Vickers, L.; Van Riessen, A. Performance of fibre reinforced, low density metakaolin geopolymers under simulated fire conditions. *Appl. Clay Sci.* **2013**, *73*, 71–77. [CrossRef]

62. Peng, X.; Shuai, Q.; Li, H.; Ding, Q.; Gu, Y.; Cheng, C.; Xu, Z. Fabrication and fireproofing performance of the coal fly ash-metakaolin-based geopolymer foams. *Materials* **2020**, *13*, 1750. [CrossRef]

63. Le, V.S.; Louda, P.; Tran, H.N.; Nguyen, P.D.; Bakalova, T.; Ewa Buczkowska, K.; Dufkova, I. Study on temperature-dependent properties and fire resistance of metakaolin-based geopolymer foams. *Polymers* **2020**, *12*, 2994. [CrossRef]

64. Le, V.S.; Szczypinski, M.M.; Hájková, P.; Kovacic, V.; Bakalova, T.; Volesky, L.; Hiep, L.C.; Louda, P. Mechanical properties of geopolymer foam at high temperature. *Sci. Eng. Compos. Mater.* **2020**, *27*, 129–138. [CrossRef]

65. Dhasindrakrishna, K.; Pasupathy, K.; Ramakrishnan, S.; Sanjayan, J. Rheology and elevated temperature performance of geopolymer foam concrete with varying PVA fibre dosage. *Mater. Lett.* **2022**, *328*, 133122. [CrossRef]

66. Masi, G.; Rickard, W.D.; Bignozzi, M.C.; van Riessen, A. The influence of short fibres and foaming agents on the physical and thermal behaviour of geopolymer composites. *Adv. Sci. Technol.* **2014**, *92*, 56–61.

67. Li, H.; Peng, X.; Li, J.; Li, L.; Hu, D.; Xiang, Y.; Han, L.; Xu, Z. Preparation and fireproofing performance of the wollastonite-metakaolin-based geopolymer foams. *Mater. Lett.* **2022**, *307*, 131020. [CrossRef]

68. Singh, S.; Singh, N. Reviewing the carbonation resistance of concrete. *J. Mater. Eng. Struct.* **2016**, *3*, 35–57.

69. Loon, L.Y.; Zaidi, A.M.A.; Boon, K.H.; Sulaiman, S.; Adnan, S.H.; Rahman, I. Carbonation and water permeability of foamed concrete. *Int. J. Sustain. Constr. Eng. Technol.* **2010**, *1*, 33–46.

70. Dapkus, G.; Stankevičius, V. Cellular concrete carbonation. *Batim. Int. Build. Res. Pract.* **1985**, *3*, 184–187. [CrossRef]

71. Namsone, E.; Šahmenko, G.; Korjakins, A. Durability properties of high performance foamed concrete. *Procedia Eng.* **2017**, *172*, 760–767. [CrossRef]

72. Park, B.; Choi, Y.C. Investigation of carbon-capture property of foam concrete using stainless steel AOD slag. *J. Clean. Prod.* **2021**, *288*, 125621. [CrossRef]

73. Tian, T.; Yan, Y.; Hu, Z.; Xu, Y.; Chen, Y.; Shi, J. Utilization of original phosphogypsum for the preparation of foam concrete. *Constr. Build. Mater.* **2016**, *115*, 143–152. [CrossRef]

74. Brady, K.; Watts, G.; Jones, M.R. *Specification for Foamed Concrete*; TRL Limited Crowthorne: Wokingham, UK, 2001.

75. Jones, M.; McCarthy, A. Behaviour and assessment of foamed concrete for construction applications. In Proceedings of the International Conference on the Use of Foamed Concrete in Construction, Dundee, UK, 5 July 2005; pp. 61–88.

76. Van Rooyen, A.S. *Mechanics and Durability of Surface Treated Structural Foamed Concrete*; Stellenbosch University: Stellenbosch, South Africa, 2020.

77. Mohammad, M.; Paivo, K.; Zahra, A.; Lidija, K.; Vilma, D.; Ahmad, A.; Mirja, I. Impacts of casting scales and harsh conditions on the thermal, acoustic, and mechanical properties of indoor acoustic panels made with fiber-reinforced alkali-activated slag foam concretes. *Materials* **2019**, *12*, 825. [CrossRef]

78. Chica, L.; Alzate, A. Cellular concrete review: New trends for application in construction. *Constr. Build. Mater.* **2019**, *200*, 637–647. [CrossRef]

79. Zhao, D.; Li, X.N.; Yan, H.C. The effect of pore structure and water absorption on carbonation resistance of sulphoaluminate cement foam materials. *Key Eng. Mater.* **2017**, *726*, 581–585. [CrossRef]

80. Singh, G.B.; Scrivener, K.L. Investigation of phase formation, microstructure and mechanical properties of LC3 based autoclaved aerated blocks. *Constr. Build. Mater.* **2022**, *344*, 128198. [CrossRef]

81. Zhang, Z.; Provis, J.L.; Reid, A.; Wang, H. Geopolymer foam concrete: An emerging material for sustainable construction. *Constr. Build. Mater.* **2014**, *56*, 113–127. [CrossRef]

82. Škvára, F.; Kopecký, L.; Myšková, L.; Šmilauer, V.; Alberovská, L.; Vinšová, L. Aluminosilicate polymers–influence of elevated temperatures, efflorescence. *Ceram. Silikáty* **2009**, *53*, 276–282.

83. Dhasindrakrishna, K.; Pasupathy, K.; Ramakrishnan, S.; Sanjayan, J. Progress, current thinking and challenges in geopolymer foam concrete technology. *Cem. Concr. Compos.* **2021**, *116*, 103886. [CrossRef]

84. Abd, A.M.; Jarullah, D.S. Producing lightweight foam concrete building units using local resources. *Civ. Environ. Res.* **2016**, *8*, 54–63.

85. Zhang, Z.; Provis, J.L.; Reid, A.; Wang, H. Fly ash-based geopolymers: The relationship between composition, pore structure and efflorescence. *Cem. Concr. Res.* **2014**, *64*, 30–41. [CrossRef]

86. Luhar, I.; Luhar, S. A comprehensive review on fly ash-based geopolymer. *J. Compos. Sci.* **2022**, *6*, 219. [CrossRef]

87. Şahin, M.; Erdoğan, S.T.; Bayer, Ö. Production of lightweight aerated alkali-activated slag pastes using hydrogen peroxide. *Constr. Build. Mater.* **2018**, *181*, 106–118. [CrossRef]

88. Abousnina, R.; Manalo, A.; Lokuge, W.; Zhang, Z. Effects of light crude oil contamination on the physical and mechanical properties of geopolymer cement mortar. *Cem. Concr. Compos.* **2018**, *90*, 136–149. [CrossRef]

89. Xue, X.; Liu, Y.-L.; Dai, J.-G.; Poon, C.-S.; Zhang, W.-D.; Zhang, P. Inhibiting efflorescence formation on fly ash–based geopolymer via silane surface modification. *Cem. Concr. Compos.* **2018**, *94*, 43–52. [CrossRef]

90. Bayraktar, O.Y.; Yarar, G.; Benli, A.; Kaplan, G.; Gencel, O.; Sutcu, M.; Kozłowski, M.; Kadela, M. Basalt fiber reinforced foam concrete with marble waste and calcium aluminate cement. *Struct. Concr.* **2023**, *24*, 1152–1178. [CrossRef]

91. Rokiah, O.; Khairunisa, M.; Youventharan, D.; Arif, S.M. Influence of processed spent bleaching earth on the durability of foamed concrete in acidic environment. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *244*, 012024. [CrossRef]

92. Makul, N. Foamed concrete containing industrial wastes. In *Handbook of Sustainable Concrete and Industrial Waste Management*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 3–21.

93. Li, J.; Sun, Z.; Pang, M.; Tian, J.; Ling, Y.; Luo, S.; Li, F. Study on preparation and durability of phosphogypsum composite cementitious foam concrete. *J. Phys. Conf. Ser.* **2020**, *1646*, 012102. [CrossRef]

94. Madhwani, H.; Sathyan, D.; Mini, K. Study on durability and hardened state properties of sugarcane bagasse fiber reinforced foam concrete. *Mater. Today Proc.* **2021**, *46*, 4782–4787. [CrossRef]

95. Zhang, S.; Cao, K.; Wang, C.; Wang, X.; Wang, J.; Sun, B. Effect of silica fume and waste marble powder on the mechanical and durability properties of cellular concrete. *Constr. Build. Mater.* **2020**, *241*, 117980. [CrossRef]

96. Kejkar, R.B.; Madhukar, A.; Agrawal, R.; Wanjari, S.P. Performance evaluation of cost-effective non-autoclaved aerated Geopolymer (NAAG) blocks. *Arab. J. Sci. Eng.* **2020**, *45*, 8027–8039. [CrossRef]

97. Delair, S.; Prud'homme, É.; Peyratout, C.; Smith, A.; Michaud, P.; Eloy, L.; Joussein, E.; Rossignol, S. Durability of inorganic foam in solution: The role of alkali elements in the geopolymer network. *Corros. Sci.* **2012**, *59*, 213–221. [CrossRef]

98. Top, S.; Altıner, M.; Vapur, H. Properties of alkali-activated lightweight concrete. In *Handbook of Advances in Alkali-Activated Concrete*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 345–367.

99. Priyatham, B.; Lakshmayya, M.; Chaitanya, D. Review on performance and sustainability of foam concrete. *Mater. Today Proc.* **2023**. [CrossRef]

100. Jones, M.; McCarthy, A. Utilising unprocessed low-lime coal fly ash in foamed concrete. *Fuel* **2005**, *84*, 1398–1409. [CrossRef]

101. Ranjani, G.I.S.; Ramamurthy, K. Behaviour of foam concrete under sulphate environments. *Cem. Concr. Compos.* **2012**, *34*, 825–834. [CrossRef]

102. Jones, R.; Zheng, L.; Yerramala, A.; Rao, K.S. Use of recycled and secondary aggregates in foamed concretes. *Mag. Concr. Res.* **2012**, *64*, 513–525. [CrossRef]

103. Mamun, M.; Bindiganavile, V. Sulphate resistance of fibre reinforced cement-based foams. *Constr. Build. Mater.* **2011**, *25*, 3427–3442. [CrossRef]

104. Liu, J.; Huang, Z.Y.; Liu, R.Q.; Hou, T.B. Research on preparation of sulfate resistance foam concrete. *Green Build. Mater. Civ. Eng.* **2015**, *2*, 158–164.

105. Chen, Y.-g.; Guan, L.-l.; Zhu, S.-y.; Chen, W.-j. Foamed concrete containing fly ash: Properties and application to backfilling. *Constr. Build. Mater.* **2021**, *273*, 121685. [CrossRef]

106. Othman, R.; Muthusamy, K.; Duraisamy, Y.; Sulaiman, M.A.; Putra Jaya, R.; Ahmad Abdul Ghani, N.A.; Mangi, S.A. Evaluation of the sulphate resistance of foamed concrete containing processed spent bleaching earth. *Eur. J. Environ. Civ. Eng.* **2022**, *26*, 3632–3647. [CrossRef]

107. Mamun, M.; Batool, F.; Bindiganavile, V. Thermo-mechanical properties of fibre reinforced cement-based foam exposed to sulphate. *Constr. Build. Mater.* **2014**, *61*, 312–319. [CrossRef]

108. Kearsley, E.; Booysens, P. Reinforced foamed concrete—Can it be durable? *Concr. Beton* **1998**, *91*, 5–9.

109. Amran, M.; Huei Lee, Y.; Vatin, N.; Fediuk, R.; Poi-Ngian, S.; Yong Lee, Y.; Murali, G. Design efficiency, characteristics, and utilization of reinforced foamed concrete: A review. *Crystals* **2020**, *10*, 948. [CrossRef]

110. Bagheri, A.; Rastegar, M.M. Effects of foam content on chloride ingress and steel corrosion in foamed concrete. *Mag. Concr. Res.* **2021**, *73*, 356–365. [CrossRef]

111. Rastegar, M.M.; Bagheri, A. Effect of foam volume on penetration parameters of foamed concrete. *Mag. Concr. Res.* **2022**, *74*, 989–998. [CrossRef]

112. Gopalakrishnan, R.; Sounthararajan, V.; Mohan, A.; Tholkapiyan, M. The strength and durability of fly ash and quarry dust light weight foam concrete. *Mater. Today Proc.* **2020**, *22*, 1117–1124. [CrossRef]

113. Wasim, M.; Roychand, R.; Barnes, R.T.; Talevski, J.; Law, D.; Li, J.; Saberian, M. Performance of Reinforced Foam and Geopolymer Concretes against Prolonged Exposures to Chloride in a Normal Environment. *Materials* **2022**, *16*, 149. [CrossRef]
114. Shi, D.; Geng, Y.; Li, S.; Gao, J.; Hou, D.; Jin, Z.; Liu, A. Efficacy and mechanism of graphene oxide modified silane emulsions on waterproof performance of foamed concrete. *Case Stud. Constr. Mater.* **2022**, *16*, e00908. [CrossRef]
115. Tran, N.P.; Nguyen, T.N.; Ngo, T.D.; Le, P.K.; Le, T.A. Strategic progress in foam stabilisation towards high-performance foam concrete for building sustainability: A state-of-the-art review. *J. Clean. Prod.* **2022**, *375*, 133939. [CrossRef]
116. Wasim, M.; Ngo, T.D.; Law, D. Durability performance of reinforced waste-based geopolymer foam concrete under exposure to various corrosive environments. *Case Stud. Constr. Mater.* **2021**, *15*, e00703. [CrossRef]
117. Khan, Q.S.; Sheikh, M.N.; McCarthy, T.J.; Robati, M.; Allen, M. Experimental investigation on foam concrete without and with recycled glass powder: A sustainable solution for future construction. *Constr. Build. Mater.* **2019**, *201*, 369–379. [CrossRef]
118. Krishna Kumar, P.; Chinnaraju, K. Utilization potentials of a nano bio-carbonate filler to mitigate alkali-aggregate reactivity of glass powder–foamed concrete. *Can. J. Civ. Eng.* **2022**, *49*, 1569–1581. [CrossRef]
119. Massekh, N.B.; Hillal, A.A. Alkali-Silica. Reaction Of Foamed. Concrete Containing. Waste Glass as Aggregate. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *961*, 012009. [CrossRef]