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Review

Foam concrete with mineral additives: from microstructure to mechanical/physical properties, workability and durability

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A R T I C L E I N F O

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A B S T R A C T

This paper explores foam concretes produced from cement, sand, water, foaming agents and secondary cementitious materials (SCMs). We examine the effects of these constituents on the microstructure, mechanical/physical properties, workability, and the durability of foam concrete. The contributions of SCMs are assessed based on their pozzolanic activity. Various SCMs, through their pozzolanic reactivity, contribute significantly to pore refinement, matrix densification, and the enhancement of mechanical strength, thermal conductivity and durability characteristics, including resistance to water ingress, chloride penetration, and sulfate attack of foam concrete mixes. While the SCMs incorporation leads to improved strength, it may also increase brittleness, which can be balanced with the addition of fibers. Furthermore, the workability is greatly affected by the incorporation of SCMs, which often have a negative effect on reducing it. The paper highlights the opportunities to use metakaolin as an SCM for the optimization of foam concrete mechanical, durability and thermal properties.

1. Introduction

The building and construction industry accounts for ~38% of CO_2 emissions and 35% of global energy consumption [1]. With increasing global population growth and the growing demand for infrastructure, the current trends in CO_2 emissions and global energy consumption could be worsened by the growing demand for construction materials. There is, therefore, a need for new materials that can be produced in large quantities, with raw materials that are energy efficient. There is also a need for large industrial production processes with low greenhouse gases (GHGs) and minimal environmental pollution. There is, therefore, a need for sustainable approaches that will reduce the carbon footprints associated with the manufacturing of concrete materials [2].

Within this context, eco-friendly building materials and technologies are gaining traction [3]. Foam concrete is a lightweight construction material characterized by it high air voids, high flowability, excellent thermal and acoustic insulation, superior fire resistance, and adequate compressive strength [4]. It reduces the dead loads of structures, reduces labour use, reduces heat losses, and increases thermal comfort [5]. In practice, foam concrete structures have been manufactured with densities between 300 and 1800 kg/m^3 [6,7]. The basic constituents of foam concrete are cement, sand, water, and foam. The utilization of SCMs such as Silica Fume (SF), bottom ash, Fly Ash (FA), quarry dust, rice husk ash (RHA), Sugarcane Bagasse Ash (SBA), and Metakaolin (MK) [8–14] has proven to improve the properties of foam concrete through pozzolanic reaction, nucleation, micro-filling effect which densify the cementitious matrix, refine the pore structure and amplifies the formation of C-S-H and C-A-(S)-H gels [15]. These mineral admixtures replace part of the PC or natural sand, offering environmental, economic, and social advantages that contribute to sustainable development [7,16,17]. However, there is little information available on how SCMs affect the microstructure and performance of foam concrete, especially in harsh environmental settings. There is also a lack of durability data and little understanding of how to optimize SCMs for improved performance [18].

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For example, the different admixtures (SF, FA) that are used to substitute for sand and cement in foam concretes, have been shown to improve compressive strength, water absorption and thermal conductivity [14]. Similarly, Krishnan and Anand [10] have shown that the strengths of bottom ash samples are greater than those produced from quarry dust, due to the small pores size of the bottom ash specimens. Also, the properties of foam concrete depend on the stability of the foaming agent, either synthetic or protein-based as reported by Sahu et al. [19] and Tran et al. [20]. Furthermore, Huang et al. [21] have reported that foam stability is dependent on the effects of different mineral admixtures that are added to the foam concrete admixture. The strengths also depend on the fineness of the powders, amorphous phase content, chemical composition, the type of ions in the admixtures and the mechanical/physical properties of the particles.

Geopolymer foam concretes are one of the advanced technologies developed recently in the construction industry. Thus, recent foam concrete fabrication methods use geopolymers as sustainable and durable materials for the replacement of ordinary Portland cement (OPC) [22–25]. However, there is a need for further work in this area.

Fu et al. [26] have presented a review of foam concrete constituent parts, production processes, and material characteristics that include stability, pore structure, drying shrinkage, and compressive strength. Their work included a state-of-the-practice review of foam concrete applications in tunnel and underground engineering. Gencel et al. [4] have also summarized some properties of foam concrete, such as fresh state, consistency, strength, and durability of foam concrete. The study's primary findings highlight the current state of cement-based foam concretes and their existing limitations, which warrant further investigation.

Additionally, the effects of fibers on foam concrete characteristics and the acoustic properties of foam concretes emerge as key areas for future research. A review of foam concrete durability characteristics has also been conducted by Zhou and Su [27]. Their work focused on the durability of several types of foam concrete, such as geopolymer foam concrete (GFC), sulphoaluminate cement (SAC), magnesium phosphate cement (MPC), and limestone calcined clay cement (LC^3). Although these works introduce the effect of the SCMs in foam concrete properties, there is a lack of a comparative framework that evaluates the performance of various SCMs in foam concrete mixtures under consistent parameters. Additionally, there is a lack of information on the effect of the SCMs on the durability (chloride and sulfate ingress) of foam concrete, which affects its performance.

This review explores the effects of SCMs, processing parameters and compositional variables on the porosity, mechanical/physical properties and the durability of foam concretes. These include the effects of foam concrete process variables on microstructure, porosity, drying shrinkage, compressive strength, durability and stability. The review also highlights the beneficial effects of metakaolin as an SCMs that can be used in the engineering of foam concrete with attractive combinations of mechanical, durability and thermal properties.

2. Foam concrete

2.1. Processing methods

Foam concrete can be obtained either by chemical or mechanical foaming methods. In the chemical method, the gas-foaming method is mainly used, while the mechanical foaming method is divided into two processes, i.e. the pre-foaming and the mix-foaming methods [28].

2.1.1. Chemical foaming method

Chemical foaming involves adding a foaming agent to the concrete mix that reacts chemically to produce gas bubbles. Sodium hypochlorite (NaOCl), hydrogen peroxide (H_2O_2), and various metal powders, like zinc or aluminum, are frequently used as foaming agents. These materials break down and react with the base material to produce gas, which creates different-sized and shaped pores in the foam concrete [29,30] .

The reactions associated with the gas formation (for H_2O_2 and Al powder) are presented in Eq. (1) and 2. This method is suitable for the formation of foam concretes with densities less than 1000 kg/m.^{3} Also, the size distributions of the pores have been found to be dependent on the type of foaming agent and the amount of foaming agent.

For instance, Hlaváček et al. [31] used aluminum powder in the formulation, creation, and refinement of the foam. Their research indicates that, during the activation phase, hydrogen is released, forming a network of closed pores. In their study, Masi et al. [32] used a method of synthesis that incorporated hydrogen peroxide (H_2O_2), aluminum powder, and a mix of different foaming agents, along with the surfactant Sika® Lightcrete 02. Their objective was to produce foams that exhibited a uniform pore structure. Their findings revealed that a 0.1 wt% concentration of H_2O_2 resulted in a uniform distribution of macropores. However, when the concentration was increased to 0.4% wt%, the pores collapsed.

$$H_2O_2(l)\rightarrow 2H_2O\ (l) + O_2(g) \quad (1)$$

$$Al\ (s) + 3H_2O(l) + OH^-(aq.)\rightarrow Al(OH)^{4-}(aq.) + 3/2H_2(g) \quad (2)$$

2.1.2. Mechanical foaming

Mechanical foaming can be carried out using two main methods: the prefoaming method and the mix-foaming method. In the preforming process (the most widely used process), the air voids are created by adding foam obtained from a foam generator to the cement-based slurry. In the case of the mix-foaming method, all of the ingredients, including the cement, foaming agent, and water, are mixed, and during the mixing process, cells appear in the structure [33].

Both methods allow for improved control of the density and distribution of air bubbles. The air bubbles tend to be more uniformly distributed throughout the material, thus improving consistency of the mix [4]. The absence of chemical reactions in the foaming process also minimizes the potential for unexpected variability in the material properties [34]. However, it is worth noting that the mechanical foaming process requires specialized equipment to generate and incorporate the foam, which can be a barrier to some producers. The process requires skilled labour to ensure that the foam is mixed correctly and consistently [35]. Particularly in low-resource or small-scale construction situations, the need for specialized equipment for mechanical foaming and the need for experienced labour might raise initial production costs and restrict the widespread use of foam concrete. Despite its performance advantages, these factors might prevent its widespread adoption, making it more appropriate for large-scale or industrial projects with technological resources available.

2.2. Applications

Foam concrete versatility allows it to be adapted for various construction needs, from lightweight insulation to load-bearing structures. Its applications continue to expand as researchers explore new manufacturing methods and admixtures. The main advantages of foam concrete are its higher energy preservation and excellent functional capacity.

Typically, plastic densities of foam concrete are between 400 kg/m^3 and 1600 kg/m^3 [36]. However, studies have shown that FC can be manufactured with densities less than 300 kg/m^3 [37]. Low-Density FC (400–600 kg/m^3), is commonly used as filling and insulating material due to its lightweight nature. Medium-density foam concrete (600-1200 kg/m^3) is suitable for non-load-bearing applications such as precast blocks, panels for outer leaves of buildings, thermal and sound insulation, and partition walls. Foam concrete with high density (1200-1600 kg/m^3) can be used for load-bearing purposes such as structural walls, foundations, flooring systems, and roof slabs [38,39]. Table 1 shows the classification of foam concrete based on the density.

Table 1
Applications of foam concrete based on the density [38,39].

Characteristics	Density range (kg/m^3)	Applications
Low density	400–600	Filling and insulating material
Medium density	600–1200	Non-load-bearing applications: precast blocks, panels for outer leaves, thermal and sound insulation, and partition walls
High density	1200–1600	Load-bearing: structural walls, foundations, flooring systems, and roof slabs

In regions with housing shortages or where traditional construction materials are scarce, foam concrete provides an alternative. Its lightweight nature makes it easier to transport and use in areas with limited infrastructure. Foam concrete is particularly useful in earthquake-prone regions due to its ability to absorb impact and dynamic loads [40]. It provides stability and minimizes damage during seismic events. This can be attributed to the presence of internal pores within the foam concrete, which contributes to its ability to absorb shocks and dissipate energy [41,42]. Additionally, due its closed pore, its fire resistance and water repellence [23,43,44] make it suitable for adverse weather conditions and hurricanes.

Foam concrete can also be used as soil stabilizer in the road subbase, acoustic, thermal, and fire insulation, renovation of old buildings, precast panels, and lightweight blocks as well [38]. Furthermore, because of the relatively higher cost of the other insulating materials (wood, dry wall, etc.) [45,46], foam concrete has become an area of interest to researchers.

3. Workability

The slump workability test commonly employed in normal concrete is ineffective for low-density foam concrete. Foam concrete flow time and consistency are assessed by using the Marsh cone as shown in Fig. 1 and the mini-slump cone. A foam concrete mixture is workable if it is self-flowing and self-compacting. According to ASTM C359–13 (2013) [47], the percentage of the flow of foam concrete using a mini-slump test is between 80 and 120%. Foam concrete with a flow time of less than 20 seconds, has a good consistency [48].

The spreadability of foam concrete has been investigated (to measure the consistency of the base mix) using the mini-slump cone test [10]. The percentage of flow varied from 90 to 125 %. Although changes in filler content had little effect on workability, changes in foam volume had significant effects on the workability. The workability was also influenced by the foam percentage in volume. With the increased percentage of foam, the mixtures became stiffened, requiring a high Water/Solid (w/s) ratio. The workability was also found to improve with blends containing quarry dust at lower w/s ratios [10]. Similarly, Gencel et al. [49] observed a decrease in flowability of about 6% when the foam content increased from 50 kg/m^3 to 100 kg/m^3 due to the increased amounts of stable air bubbles at high foam content. The study also highlighted the increase in workability with the increase of glass sand up to 100% replacement, as depicted in Fig. 2. The enhancement in workability with the glass sand content was attributed to the glass particles smooth surface. In another study, it was found that when the amount of foam in the mixture increased, the amount of solids decreased, resulting in greater slump values [50]. Furthermore, when FA replaced OPC, the slump flow improved due to FA smooth and spherical particles. Hemp fibers, in contrast, decreased slump values because of their propensity to absorb more water, which reduced the mix workability.

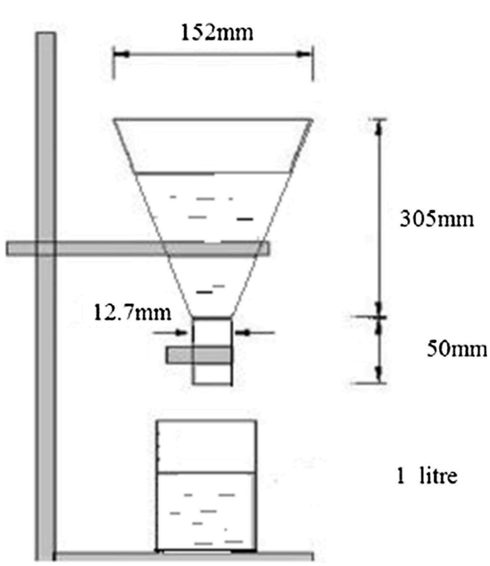

Fig. 1. Schematic diagram of modified Marsh cone reported by [53].

Rheological parameters were measured with a parallel-plate rheometer as per ASTM C1749 (2012) [51]. A funnel of marsh was used to determine the time taken by the various foam concrete blends to flow. Bagheri and Samea [52] assessed the workability of these specimens as a function of 0, 20, 45, 56, and 83 % of air content in foam concrete. The results showed that foam inclusion enhanced the force per unit area at the yield point stress of the base mixture (0 % foam content). This increase in yield stress can be attributed to the introduction of air bubbles, which form a dispersed structural network within the mix. These bubbles resist initial deformation, making the fresh mix more cohesive and less prone to flow, and then reducing the workability.

The plastic viscosity measurement revealed that adding 20 %vol of foam reduces the plastic viscosity of the foam concrete mixes compared to the base mix. However, the percentage of foam and the viscosity had opposite effects. Also, as the foam volume increased, the viscosity increased, and very high foam volumes resulted in the instability of the mixtures. The values of the flow times for the base mixture and the mixtures containing 20 %vol and 45 %vol foam were below 20 seconds, while the flow times for the other mixtures were above [52].

Krishna et al. [54] assessed the consistency and workability with FA being utilized as a substitute of 25%, 50%, and 75% by cement mass. There was an inverse relationship between the foam concrete consistency and the FA proportion. The workability decreased with increasing proportions of FA due to the spherical shape of the FA particles. Furthermore, when the volume of foam increased, the consistency decreased due to high cohesiveness between foam concrete mixture particles at lower densities [48].

The water-to-binder (w/b) ratio influences foam concrete flow characteristics. The flow ability of foam concrete was enhanced at a higher w/b ratio. However, there was a separation between the solid and liquid phases in the mixture [55]. The foam concrete workability, i.e., slump flow, improved as FA percentage and density were increased [54].

The addition of silica fume (SF) in foam concrete was found to greatly reduce the workability [56]. Furthermore, they noted that the increase of the length (6, 9 and 12 mm) of Glass fiber and Carbon fiber reduced the workability by around 12% to 20% due to the creation of a mesh-like network within the mix, which impedes flow and reduces workability.

Khawaja et al. [57] found that replacing 25% of cement with sugar cane bagasse ash (SCBA) in foam concrete led to a decrease in workability due to the high adsorptive capacity of sugar SCBA leading to a stiffer cement paste matrix and decreased workability. Furthermore, the mixture's internal friction was exacerbated by the irregular shape and larger surface area of SCBA particles, which decreased slump flow.

Increased slump flow over a range of fly ash (FA) replacement levels (0%, 25%, and 50%) indicates that adding waste gypsum board (WGB) as a partial cement substitute to foam concrete mixes improves workability [58]. Increasing WGB from 0% to 25% resulted in a discernible

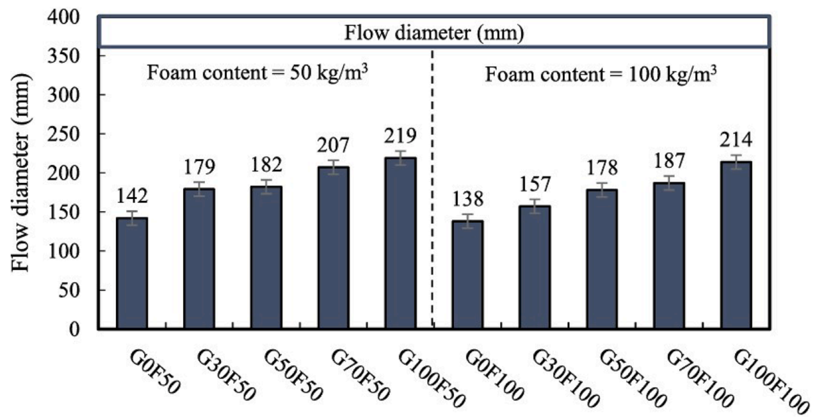

Fig. 2. Workability test results of foam concrete mixes using flow table test [49].

increase in slump flow, suggesting better mixture fluidity, while maintaining a steady water-to-cement ratio and foam content. This improvement was explained by the fact that WGB and FA have lower specific gravities than cement, which resulted in a larger binder volume, better particle coating, and less interparticle friction. Furthermore, improved internal redistribution is made possible by the moisture added by foam and the decreased water demand brought on by the lower cement amount, which further improved the workability.

Similarly, Kabbo et al. [59] noted that a combination of SF (5%) and waste marble powder (5-20%) improved the workability (slump flow and j-ring test) of foam concrete compared to the control mix. This was due to the improved packing resulting in the fine particles, as well as the lubrication from the pozzolanic reaction.

The use of 10, 20, 30, 40 and 50% reuse concrete powder (RCP) in foam concrete was found to reduce the flowability by 4.4%, 7.4%, 10.0%, 13.0%, and 14.8% compared to the control mix (0%wt). This was explained by the presence of voids in the RCP due it rough surface [60]

4. Physical properties

This section presents some physical properties of foam concretes. They include properties such as microstructure, thermal conductivity, and drying shrinkage that contribute to the performance of foam concrete.

4.1. *Drying shrinkage*

Foam concrete contains little or no coarse aggregate. Hence, its shrinkage is different from that of normal concrete. Also, since the shrinkage of concrete can lead to easy cracking, there is a need to control shrinkage, which can also lead to dimensional inaccuracy, while compromising structural integrity.

Nambiar and Ramamurthy [61] have studied the shrinkage behavior in foam concretes in which cement was replaced by FA. The resulting foam concrete shrinkage was less than that of the base mix. It was also observed that shrinkage reduced when the ratio of filler to cement was increased. This was attributed to the low volume of the aggregate content.

Furthermore, the addition of FA led to a small increase in shrinkage, although there was an improvement in compressive strength. This is probably due to the reduction of foam volume required when fly ash replaces cement and/or sand at a given density. Consequently, the proportion of shrinkable paste (cementitious material) increases, leading to higher overall shrinkage [61]. While it has been reported that a combination of lime mud and Fly ash (LM-FA) (0, 50, 60, 70 and 80 % wt) had an effect of decreasing the drying shrinkage [13]. The drying shrinkage of FC was found to be between 0.34% to 0.44%, with densities varying from 600 to 900 kg/m^3 [13]. Furthermore, the use of LM-FA from 0 to 50% led to a reduction of up 23% in drying shrinkage due to the pore refinement. A combination of LM-FA increases the filling effect and the pozzolanic reaction, which refined the pore structure, then reducing the drying shrinkage. However, when LM-FA amounts higher than 60% were used the reduction in drying shrinkage was reduced. This could be explained by the dilution effect own by a large amount of pozzolanic reaction. In the same line, it was found that the negative effect of excessive RHA (20%) on the drying shrinkage can be balanced by using 50% of Waste marble powder (WMP) as fine aggregate in foam concrete. This was attributed to the refinement of the pore due to the grain shape and pore size distribution of the WMP [62].

In another study [7], foam concrete drying shrinkage was found to increase quickly for 21 days before slowing down to a maximum of 1951 $\times 10^{-6}$ mm/mm after 90 days at 50 kg/m^3 foam content without basalt fiber (BF) because of greater porosity and evaporation rates. At 2% BF and 50 kg/m^3 foam content, adding BF dramatically decreased shrinkage by up to 32.13% because of its bridging action, moisture retention, and enhanced pore structure. However, BF marginally enhanced shrinkage by 6.12% and 2.34%, respectively, at lower foam content levels (30 and 40 kg/m^3), most likely as a result of its effect on decreasing porosity.

In their work, Yang et al. [63] used eco-friendly additives such as Recycled Mortar Powder (RMP) and recycled concrete powder (RCP) to partially replace cement in FC mixtures. They studied the effects of these additives on 15-day drying shrinkage. When compared to the control mixes, the 15-day dry shrinkage in the mixes with 7.5% and 15% RCP were 10.5 and 5.1% lower, respectively, while the mixture containing 30% RCP had a 15-day shrinkage that was 4.7% higher.

RMP incorporation reduced the drying shrinkage. Compared to the control group, foam concrete with 7.5%, 15%, and 30% RMP had 15-day shrinkage values that were 9.5%, 6.1%, and 0.3% lower, respectively. The SCMs used comprised of high amount of micro-hardness calcite and quartz grains, hence, reducing the drying shrinkage of the foam concrete [64]. Although the RP additions were recognized to be beneficial to foam concrete, a high volume (30%) of RCP was harmful to foam concrete performance, which then increased the drying shrinkage.

Zhang et al. [65] investigated the effects of silt content (0, 20, 30, 40%), wet density effect (600, 700, 800 kg/m^3), and coarse particle content (25, 30, 35, 40%) on the drying shrinkage of foam concrete. They concluded that, when the amount of silt and coarse particles increased, the drying shrinkage reduced. The observed shrinkage occurred due to two main factors that occurred during the cement hydration and hardening processes. First, the cement-water system contracted, leading to a reduction in volume. Simultaneously, a thermal effect occurred as the specimen cooled, further contributing to the apparent shrinkage. Interestingly, the initial volume expanded during the earlier stages of the process.

Li et al. [66] found that ceramsite can be used as an internal curing agent to reduce the foam concrete shrinkage by reducing early cracking, which enhanced the material performance. While dry ceramsite achieves a higher 75% reduction in shrinkage but begins cracking around 7 hours earlier, pre-wetted ceramsite reduces drying shrinkage by 58% and increases the period until cracking by over 80 h. The ceramsite capacity to gradually release water makes this enhancement possible by promoting early foam stability and densifying the ITZ.

According to Ahıskalı et al. [67], adding PPF (0, 1 and 2%) had only a slight influence on the shrinkage and expansion of GFC, but substituting slag aggregates (0, 50 and 100%) for limestone reduced the drying shrinkage. These results were consistent with compressive strength results because using slag aggregates improved strength development and reduced porosity.

4.2. Thermal conductivity

The thermal insulation of foam concrete makes it an attractive material in the construction of light weight concrete structures. Such thermal insulation characteristics can be managed by the control of foam density and the properties of the concrete struts; there is an opportunity to develop foam concrete structures with attractive thermal insulation properties and mechanical properties.

Foam concrete thermal conductivity has been widely studied [23,63, 68–70]. The studies have shown that thermal conductivity is dependent on factors such as porosity, density, moisture content, air-void size, distribution, binder type and composition, and filler content. For example, it was pointed out that thermal conductivity increased when the moisture content increased because water has higher thermal conductivity than air [71].

The normal thermal conductivity of concrete is approximately 5-30 % greater than that of FC. This is due to the higher pore densities in the foam concrete structure. For foam densities between 600-1600 kg/m^3, the thermal conductivity is between 0.1-0.7 W/(m. K) [72].

Batool and Bindiganavile [73] have studied the effects of pore size parameters (D50 and D90) on FC thermal conductivity. Their results showed thermal conductivity decreased with the augmentation of median pores (D50, median pore size). In addition, they observed a better correlation between D50 and thermal conductivity than the correlation with D90 (90th percentile size). They also noted that the thermal conductivity was more affected by small pores than they were by bigger ones. Furthermore, the type of pozzolanic additives had little correlation with the thermal conductivity at a given foam concrete density, as shown in Fig. 3.

According to Yang et al. [63], the thermal conductivity coefficient did not depend on the dosage of reused eco-friendly additives, such as RCP and RMP. However, the thermal conductivity was affected by pore size and shape. Furthermore, when the two types of additives are compared, the differences in thermal conductivity are not significant. The thermal conductivity of RCP and RMP (0, 7.5, 15, and 30%) varied from 0.068 to 0.072.

According to Singh [25], the reduction in thermal conductivity that occurs in decreasing density can be attributed to the limited amount of water that is chemically bonded in the gel pores of the geopolymer.

Also, foam concretes with polypropylene fibers (PPF) have thermal conductivities that are lower than those of carbon fibers [44]. This is due to the uniform repartition of air voids into PPF based foam concrete mixes [6]. Furthermore, the thermal conductivities were also affected by dry, wet density, and porosity [44]. The incorporation of Basalt fibers of up to 3% reduced the thermal conductivity by up to approximately 2% [63].

Gencel et al. [63] revealed that the addition of 15% of SF led to an increase in the thermal conductivity by approximately 4%, which was attributed to the reduction in porosity due to the incorporation of SF. Similarly it was reported an increase of approximately 37% in thermal conductivity when SF was used in foam concrete [14]. In contrast, when FA was used to replace cement (0-50%), the dry density and then, the thermal conductivity reduced [50]. The most significant decreases were noted in mixtures with 30%, 40%, and 50% FA, paired with foam contents of 50, 75, and 100 kg/m^3, respectively. Porosity and dry density have a significant impact on thermal conductivity in concrete; higher porosity and lower thermal conductivity are generally associated with lower dry density. The material porosity is increased, and its thermal conductivity is further reduced when FA is used in place of a part of the cement due to the drop in dry density. This was supported by earlier research [14], where it was found that the use of FA significantly decreased the thermal conductivity.

4.3. Effects of mineral additives on microstructure

The air-void system is one of the most important parameters that can affect foam concrete microstructure. Foam concrete pore systems can be characterized by their porosity, pore size distributions, and permeability. According to Compaoré et al. [74], porosity and microstructural characteristics have a direct impact on strength and thermal conductivity.

Bartenjeva [75] has shown that the addition of mineral additives, such as dispersed wollastonite and diopside, regulates pore sizes in foam concrete mixtures. The resulting pores are also closed. Additionally, the volume fractions of these pores increase by 47 to 49%, compared to those in the mixes without mineral additives. However, the addition of wollastonite reduced the diameter of the pores with sizes greater than 0.1 μm by 2.34 times, while the addition of diopside reduced the pore sizes by 8.2%.

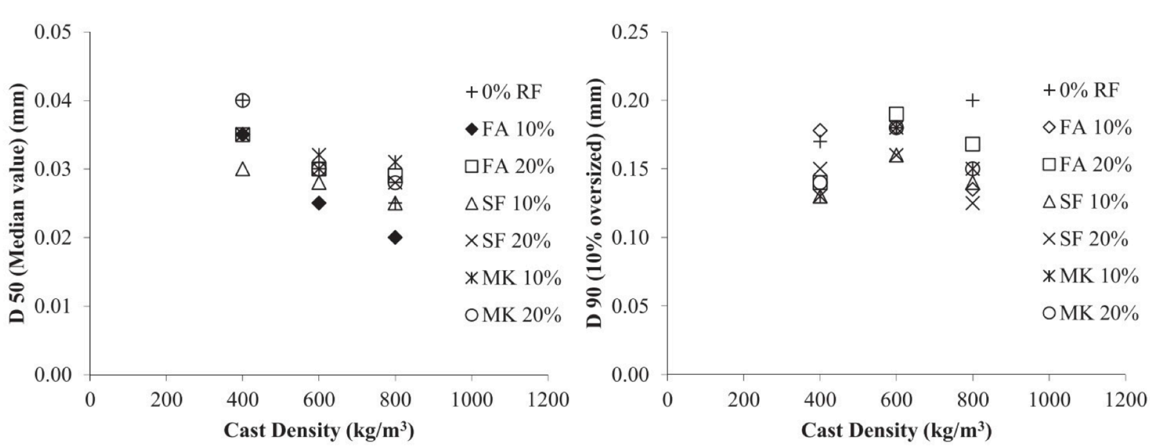

Fig. 3. Thermal Conductivity vs the Air-void Size Parameters for D50 and D90, respectively [73].

Furthermore, prior work by Yang et al. [63] has shown that RPs can be used as SCMs in foam concrete mixes. In fact, the addition of different kinds of RPs has little effect on porosity change of mixtures which did not affect the thermal conductivity. For mixtures containing 0, 7.5, 15 and 30% of RCP, the porosities were 83.15%, 82.23%, 83.07% and 83.53%, respectively, for mixtures with 0, 7.5, 15 and 30% of RMP, the porosities were 83.15%, 82.01%, 82.23% and 82.77% [63].

Zhang et al. [65] have studied the effects of silt and coarse aggregate content on foam concrete. Their work shows that silt content is the primary factor that affects pore configurations in mixtures. They also showed that coarser aggregate contents enhance pore configurations.

Krishnan and Anand [10] have shown that bottom ash-based foam concrete mixes reduce the number of large voids. They have also shown that bottom ash-based foam concrete mixes result in foam concretes with more uniform void sizes. When compared to the quarry dust mixes, they observed the opposite effect, leading to a decrease in compressive strength, as stated earlier.

Song et al. [76] found that the use of rice husk biochar (RHBC) in foam concrete as internal curing material provided more nucleation sites, which enhanced the formation of additional reaction products, which formed a more homogenous pore structure by filling the cracks. Furthermore, the addition of RHBC has been shown to improve bubble restraint force by raising the yield stress of the cement paste. This decreases bubble diameter and buoyancy, resulting in increased foam stability and mechanical performance of the foam concrete.

It was found that the microstructure of foam concrete cured for 90 days changed dramatically by the addition of SCMs, such as waste marble powder (WMP) and RHA, according to the SEM examination [62]. Mixtures containing WMP and RHA had bigger, more scattered, and better-defined C-S-H crystals than the control mix. This suggests increased hydration and pozzolanic activity, which helped create a more porous but structurally improved microstructure.

In the study by Maglad et al. [58], as shown in Fig. 4, the average pore diameter rose with increasing WGB content in the reference mixture (FA0), demonstrating that WGB alone had a limited influence on pore refinement. However, when FA was coupled with WGB, large pore content and average pore diameter were reduced by up to 10% WGB, owing to synergistic filling and pozzolanic reactions that increased C-S-H formation and refined the pore structure. Beyond 10% WGB, the mixes exhibited an increase in big pores and a decrease in tiny capillary holes, which corresponded to lower mechanical strength, increased porosity, and water absorption.

According to Zhang et al. [77], adding coal gangue (CG) to foam concrete at percentages of 10%, 20%, 30% and 40% greatly improved the pore structure. As a result of this alteration, the average pore diameter, the percentage of large pores, and the pore connectivity decreased as shown in Fig. 5. These enhancements were ascribed to CG pozzolanic activity and filling effect.

5. Mechanical properties

5.1. Compressive strength

Due to the absence of coarse aggregates, the foam concrete failure mechanism differs from that of normal concrete. As stated earlier, SF and FA as additives improve foam concrete compressive strength. This is due to the pozzolanic activity, hence, reducing the porous zone formation between the matrix-aggregate bonds. This increases the interlock zone between the paste-aggregates (Interfacial Transition Zone ITZ). These are illustrated in Fig. 6 with a foam concrete density of 1300 kg/m^3 [78].

The utilization of 10% MK resulted in a stabilized compressive strength of foam concrete specimens at higher temperatures (400, 500, and 600 °C). All mixes with 15% MK for 400 °C exhibited higher 28-day strengths. However, the strengths reduced with increasing temperature between 500 and 600 °C [43]. The filler type determined the w/s ratio at a given density. Also, the strengths improved with decreasing sand particle size [79].

Foam concrete composites (consisting of FA and PPF) with densities varying from 800 to 1500 kg/m^3 had compressive strengths of 10-50 MPa. The 28-day mix strengths (without FA) increased by 70–75 %, when compared with the 7-day mix strength, while the same mixes with SF resulted in 28-day strengths that were approximately 85-90 % of the 7-day mix strength [33].

Krishna and Chinnaraju [44] have studied the effects of PPF and carbon fibers on foam concrete mechanical properties. In spite of the minimal reduction in density with substitution rate, the compressive strengths increased with PPF and carbon fiber reinforcement.

Another experimental study was undertaken by Zhang and Wang [24], who investigated the effects of pore characteristics and mechanical properties of geopolymer foam concrete (GFC). Their GFCs exhibited similar characteristics (air-cell structure and mechanical properties) to foam concretes produced from OPC. The addition of H_2O_2 foaming agent (in an amount varying from 0.5 to 1.5% into fly ash-based GFC slurry)

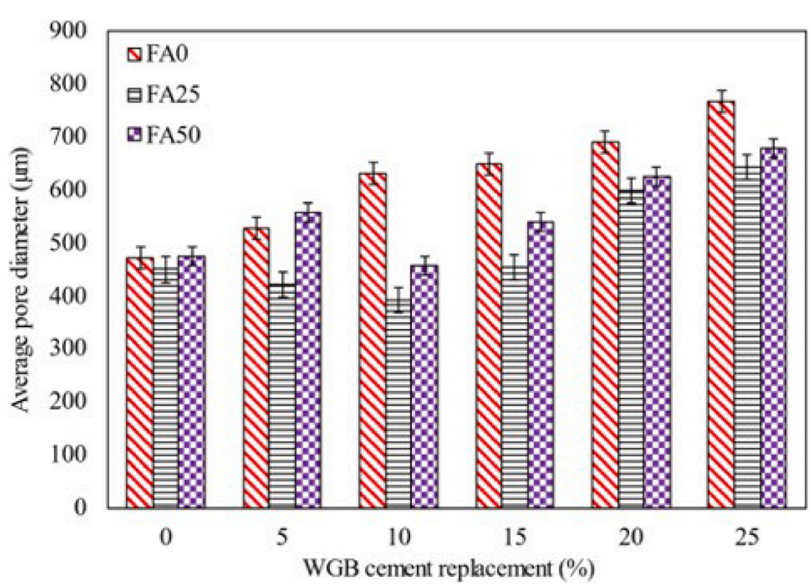

Fig. 4. Average pore diameter of foam concrete mixes [58].

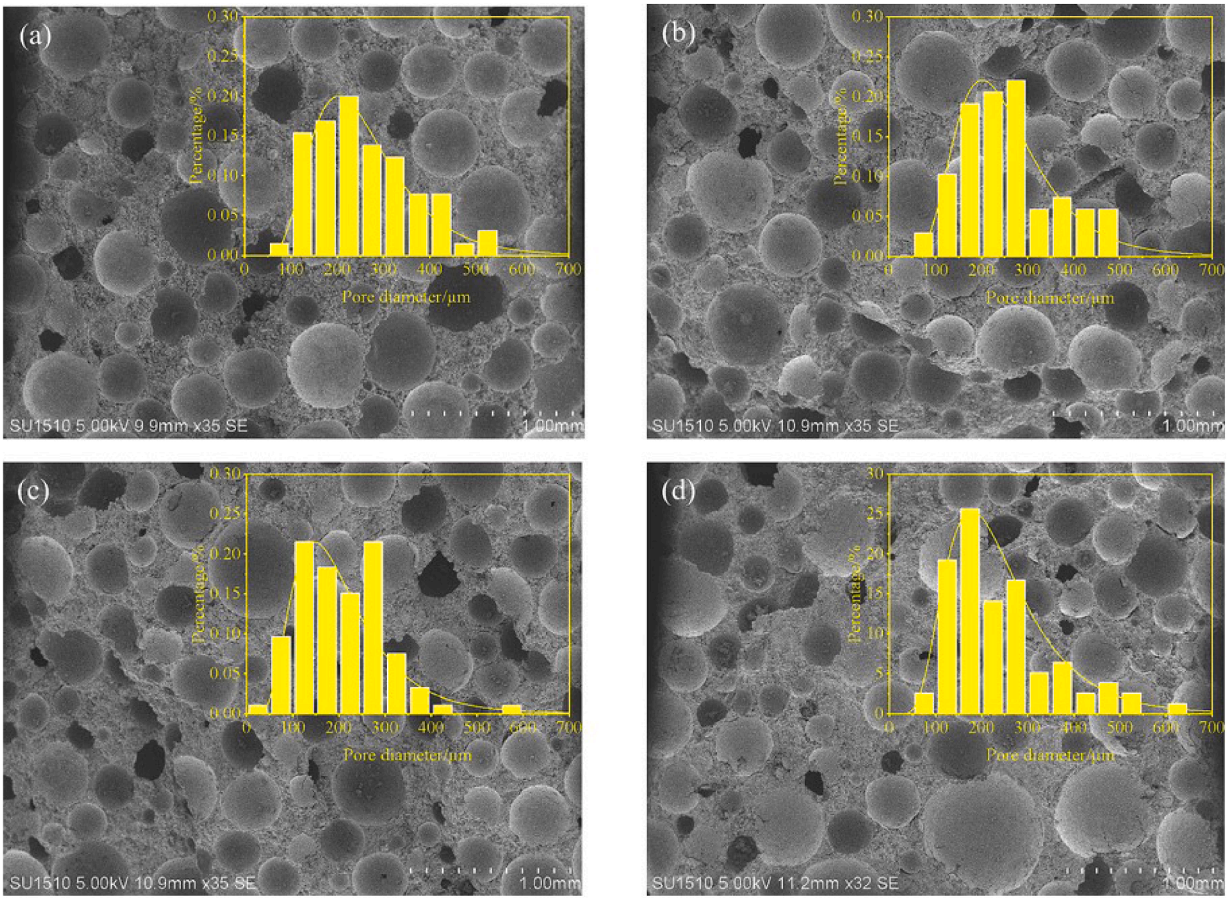

Fig. 5. Pore structure and pore size distribution of foam concrete containing CG: a) 10%, b) 20%, c) 30% and d) 40% [77].

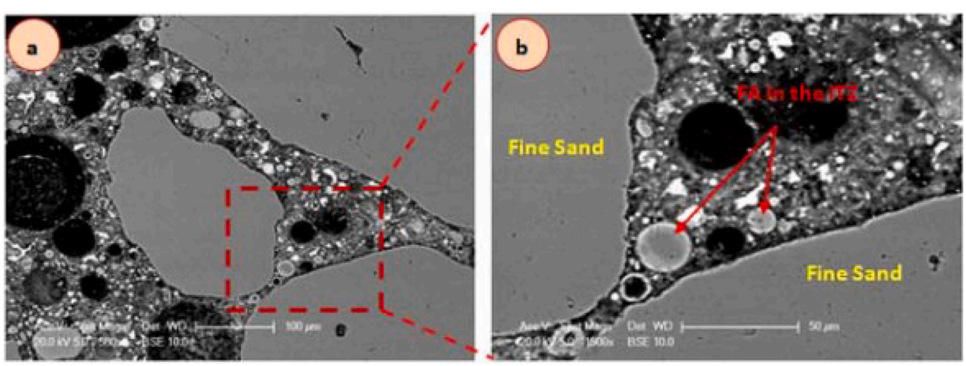

Fig. 6. 1300 kg/m3 foam concrete SEM images illustrating the increase of matrix-aggregate zone from a) to b) [71].

also reduced the foam density and strength [22,27].

Increasing mineral admixtures such as SF, FA typically results in increased brittleness in foam concrete [80]. In the presence of 15% SF, it was found that the cracking patterns change from scattered microcracks to more concentrated and localized macrocracks, which is responsible for the increased brittleness [81]. However, when lightweight aggregates are added, the brittleness is reduced [80]. When steel fibers were used in lightweight reinforced foam concrete, the failure mode remained shear brittle, but cracking and ultimate loads increased by 18.5% and 25.5%, respectively, while the displacement ductility and toughness increased by 38% and 56%, respectively [82]. Amran et al. [83] found that the incorporation of PPF in foam concrete reduced the brittleness. Similarly, Raj et al. [84] pointed out that using coir and PVA fibers in foam concrete altered the failure behavior, shifting it from brittle to ductile. The addition of basalt fibers (BF) improved the tensile properties of foam concrete, effectively reducing its brittleness and enhancing its durability, thereby making it more suitable for applications that require improved load-bearing and fracture resistance [85].

Krishnan and Anand [10] have explored the relationship between air-void size and foam concrete strength for foams with different densities (1200, 1400, and 1600 kg/m^3) that utilize industrial wastes, such as quarry dust and bottom ash. Unlike quarry dust mixes, the bottom ash mixtures enabled the creation of closed pores, leading to an increase in compressive strength. Additionally, the respective utilization of class C fly ash and Na_2SO_4 admixtures resulted in an increase in the setting time and early age strength of the mixtures.

Wang et al. [86] have improved the foam concrete compressive strength and foam concrete failure modes by incorporating ceramsite into mixtures. Two types of failure modes were observed, i.e., foam concrete failure and ceramsite failure. In fact, cracks were initiated and developed into foam concrete, while cracks were developed through ceramsite whilst foam concrete and ceramsite were crushed due to the strength between the ceramsite aggregates and foam concrete, as shown in Fig. 7 [a) 400 kg/m^3, b) 600 kg/m^3; c) 800 kg/m^3; d) 1000 kg/m^3].

Furthermore, fiber additions to foam concrete mixtures improve the flexural strength. Foam concrete without admixtures also had lower ductility than FC with mineral additives such as FA, SF, and superplasticizer [80].

Foam concrete compressive strength data from different publications [13,18,33,49,71,81,85,87–90] are plotted in Fig. 8. The results show that the compressive strength increases with increased density. Nonetheless, significant variation exists between experiments at comparable densities, most likely as a result of variations in mix composition, curing techniques, and material selection. The addition of foam in the foam concrete mix leads to an increase in porosity, which decreases density. This is because the foam volume in the foam concrete mixture increases as density decreases, creating more pores [91]. The creation of these pores is at the origin of the decline in compressive strength. However, the variation in data points across different studies suggests that density alone is not the sole determining factor. In fact, in addition to density, several other factors such as microstructure, curing period, curing condition, cement type, dosage, mixture and water-cement (W/C) and water-solid (W/S) ratios, foam percentage, type foaming agent (synthetic or protein foaming agent), additive can influence the foam concrete compressive strength [92,93]. This diversity underlines the significance of adjusting parameters outside density, such as binder concentration and additives, to maximize performance. This is also supported by the data in Table 2, obtained from a few data points given in Fig. 8 . Depending on the composition (the type of SCMs and content, the addition of fiber, the type of foaming agent, the curing conditions), the density of foam concrete varied, which impacted its mechanical properties

It was pointed out that the compressive strength increased with foaming agent content up to 3 %wt cement [89]. However, while a decline was observed when 4% of foaming agent was used for both mixes (without and those with 20% of fly ash). The work Hilal et al. [71] also revealed an increase in compressive strength, when sand in the conventional foam concrete was replaced by up to 25% of additives (FCa). This resulted in a combination of FA and SF. Further work is needed to develop our basic understanding of failure mechanisms in foam concretes with different combinations of FA and SF.

Jiang et al. [8] found that after 56 days of curing the combination of SF and MK in foam concrete achieved the highest compressive strength of 0.74 MPa with a porosity of 91.6% while the mixes with only MK had a compressive strength of 0.63 MPa and 0.60 MPa with porosities of 91.9% and 91.2%, respectively. The improvement in compressive strength with FC mixes containing SF and MK was attributed to the densification of the solid phase between the pores.

The investigations were undertaken to evaluate MK-based foam concrete compressive strength under heat, where cement was replaced with MK by 5 %, 10 %, 15 % [43] . The densities investigated were 1100, 1200, 1300 and 1400 kg/m^3. The research revealed that the mixture containing 10 % showed a stable compressive strength of specimens with and without temperature, at 400, 500 and 600°C. In addition, the mix with 15 % of metakaolin gives higher 28th-day compressive strengths at all densities for 400°C but the compressive strength decreases with the temperatures of 500 and 600°C.

5.2. Flexural strength and splitting tensile strength

Fiber reinforcement has been frequently used to enhance the tensile-related characteristics of foam concrete. Table 2 shows a few studies flexural strength from the literature.

The addition of 40% RHA and PPF can improve flexural strength and splitting tensile strength from 30 to 40% [96]. Amran et al. [83] also showed an increase of approximately 20 to 50% in flexural and splitting tensile strengths compared to the control mix when a combination of SF and PPF were used.

Li et al. [97] investigated the effects of several design factors on the tensile performance of foam concrete, including splitting and flexural characteristics. These parameters included foam concrete density (800, 1700 kg/m^3), polyvinyl alcohol fibers (PVAF) length (19, 200 µm), diameter, and content. Although rupture happened after peak loading, particularly in higher-density mixes because of shorter fiber pull-out lengths, their flexural experiments demonstrated that small fibers (19 µm) caused strain-hardening in both low-density and high-density foam concrete. Furthermore, pore shape, density, and D90 (pore size distribution) all significantly impacted splitting tensile strength and first-crack flexural strength. In particular, fracture development was facilitated by lower density, bigger pore diameters, and more irregular pore geometries, which decreased both tensile strengths.

When raffia fibers (RF) are added (0, 2, 4, 6 and 8% volume fraction of the total mix) into foam concrete slurry with a design density of 950 kg/m^3, the flexural strength of the material was enhanced [98]. The flexural strength of foam concrete containing 6% RF achieved the highest flexure at all curing times. The flexural strength for 6% RF after 28-day of curing was 1.26 MPa while for the control mix (0% RF) was 0.61 which is an improvement of 107%. In contrast, in early study, it was observed a decline of the flexural strength of foam concrete containing bottom ash (BA) and 300 kg/m^3 OPC with densities varying from 924 to 1267 kg/m^3 when polypropylene fiber (PPF) was added in amount of 0, 0.5 and 1% volume fraction [91]. The use of cement paste for fiber coating, the effect of fiber incorporation on foam concrete consolidation, and the alignment of fibers parallel to the applied load, which may contribute to void formation, were the main factors explaining the decrease in flexural strength of foam concrete mixtures with PPF [99]. When the OPC content was 400 kg/m^3, the flexural strength was improved due to the cracks bridging own by the PPF [100].

Nanofibers, such as carbon nanotubes (CNTs), are effective in inhibiting the growth of microcracks, thereby enhancing the flexural

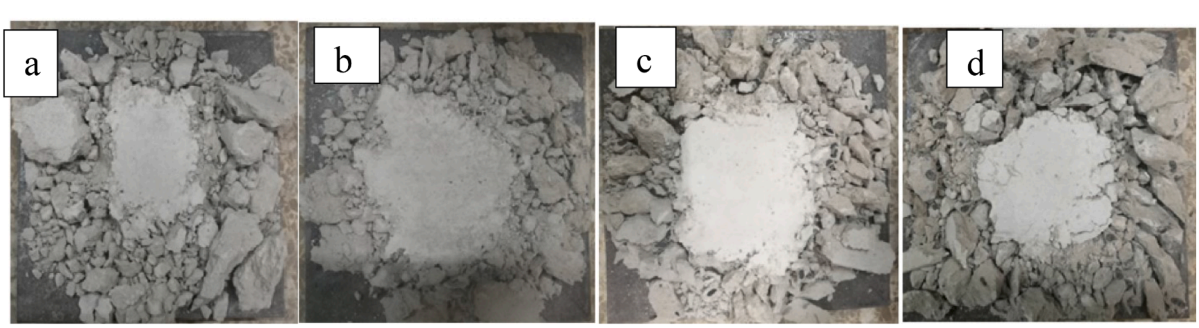

Fig. 7. The failure mechanism of foam concrete containing ceramsite [86].

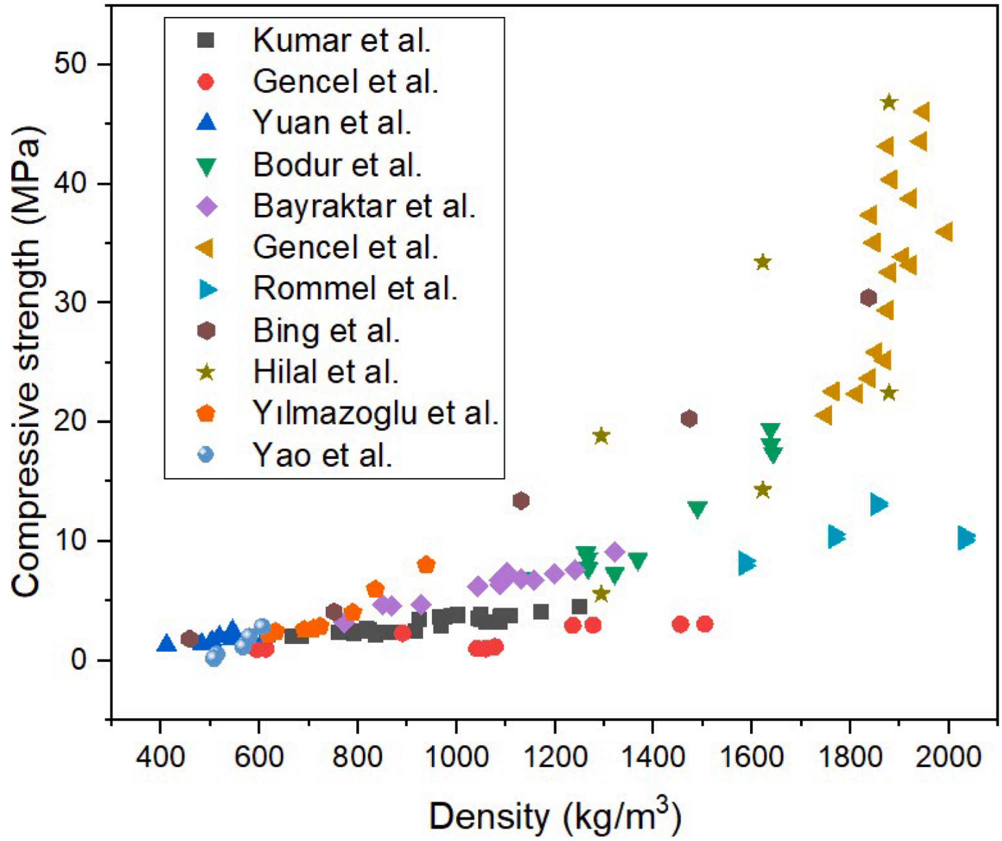

Fig. 8. Compressive strength vs density of foam concrete drawn from the literature.

Table 2
Compressive strength and flexural strength of foam concrete drawn from the literature.

References	Ingredients	Max. replacement level (%)	Density (kg/m^3)	Compressive strength (MPa)	Flexural strength (MPa)
[94]	OPC, LSW	Up to 100	667–1251	2.0-4.5	-
[49]	OPC, glass sand, expanded perlite	Up to 100	594–1504	0.95-3.07	0.45-1.25
[13]	OPC, lime mud, FA	80	411–612	1.31-2.52	-
[85]	ATP, BF	30	1130.8-1642.6	6.95-19.45	2.96-5.81
[88]	OPC, Brick, roof tile, SF	40	772–1321	3.18-9.09	0.37-1.08
[95]	OPC, SF, BF	15	1749.6-1993.6	20.6-46.1	4.30-6.91
[18]	AAFC, GBFS, FA, CZ	20	617–938	2.26-8.99	0.41-0.81

LSW: limestone slurry waste, ATP: attapulgite, CZ: clinoptilolite zeolite

strength and toughness of foam concrete [101]. The mechanical characteristics of foam concrete, such as its compressive, flexural, and splitting tensile strengths, have been demonstrated to be considerably impacted by the inclusion of silica fume and basalt fiber. In particular, adding 15% silica fume increased compressive strength by around 46%, while increasing the amount of basalt fiber from 0% to 3% increased flexural strength by up to 88% [81]

Gencel et al. [62] investigated the flexural strength of foam concrete containing glass sand (GS) (up to 100%) and foam contents of 50 and 100 kg/m^3. It was found that higher foam content (100 kg/m^3) had a less noticeable detrimental impact on flexural strength than compressive strength, with the majority of flexural strength in the studied foam concrete mixes being reached by 28 days. Because of their larger solid material composition, mixes containing 50 kg/m^3 foam consistently showed a flexural strength that was almost 55% higher than those containing 100 kg/m^3 foam. At both foam levels, adding glass sand increased flexural strength; the advantages were more noticeable at 50 kg/m^3 of foam content. This was attributed to the low porosity resulting in the addition of GS.

Hilal et al. [80] found that stronger foamed concrete, which was either made denser or had SF, FA, and superplasticizers added, showed more lateral distortion, which was demonstrated by larger cracks, before failing during the splitting tensile test.

6. Durability of foam concrete

6.1. Water absorption and permeability

Water and moisture transfer into foam concrete have been shown to greatly affect the mechanical and physical properties of foam concretes [68]. Absorption and sorptivity are terms used to describe a material's ability to absorb and transfer water. These properties can be used to identify the penetration of harmful products, such as sulfate and chloride ions, which cause concrete long-term degradation.

Basic understanding of moisture transfer (in concrete) is critical for improving the performance of concrete as a construction material [102]. Furthermore, foam concrete water absorption can be affected by numerous factors such as porosity, pore size and distribution, density, foaming agent type, moisture content, mix proportions, and curing conditions.

Gökçe et al. [14] assessed FA and SF effects on foam concrete characteristics such as water absorption. The results showed that the water absorption ranged between 3.5% and 35.9%. The addition of mineral admixture led to reduce water absorption.

The PPF addition improved foam concrete hydrophobic characteristics, leading to a decrease in adsorption and sorptivity characteristics. As the PPF percentage increased, there was a curvilinear drop in water absorption [44].

Foam concretes containing micro-silica and having densities of 500 and 700 kg/m^3 absorbed 100.9 and 64.3 % of water, respectively. This water absorption estimate by volume for the two densities was 53.6 and 42.4%, respectively [103].

The water permeability of foam concrete containing sand and brick wastes depend on the porosity, the finer the pores, the less the water permeability. Due to the evenly distributed and independent pores in some SCMs, such as toner and MK, there was a decrease in the capillarity ability to absorb water.

The distribution and fineness of the pores, as well as their porosity and strength, had an impact on the water permeability [104]. Also, adding 20% MK and toner improved capillary water absorption, but adding 30% and 50% MK had a negative impact on water permeability.

6.2. Chloride penetration

Concrete structural failure and durability deterioration are primarily caused by steel corrosion and chloride ingress [105]. Foam concrete is an extremely versatile lightweight material that is becoming more popular in structural and semi-structural applications. This would almost certainly necessitate the incorporation of reinforcing bars within the foam concrete. The presence of a large air void volume near steel may have adverse effects on its electrochemical behavior and potentially ruin the creation of the passivation film [106].

Foam concrete penetration parameters such as water absorption and chloride ingress were experimentally investigated. The volumetric and capillary absorption increase with increasing porosity, leading to a decrease in chloride ingress, when considering the concrete total volume. However, when considering the penetrable phase (paste phase), the absorption and the chloride ingress showed the same tendency [107].

Wasim et al. [108] have studied and modelled the durability of reinforced GFC exposed to different chloride concentrations (1, 3, and 5%). They observed that the corrosion was mostly induced by the temperature and the humidity. Othman et al. [109] have observed that, when PSBE was added as pozzolans into foam concrete mixtures, there was a decrease in chloride permeability. Additionally, the addition of pozzolans reduces concrete permeability to chloride more than it reduces the mixtures' w/c ratio [110]. The chloride ion tolerance of concrete is more dependent on the porosity and pore interconnectivity than the cement's chemical bonding capacity [111].

The charge (Coulomb) flowing over the calcined clay samples is found to decrease, as the calcined clay content increases up to 10%. Charge transfer, however, increases with calcined clay content at 12.5%, suggesting that substituting cement for calcined clay enhances resistance to chloride ions [112]. It was observed that, as the carbonation depth was increased, the total charge passing through decreased.

Carbonation was discovered to reduce chloride ion diffusion, suggesting that the deposit of carbon dioxide into concrete specimens reduces the surface porosity and, thus, chloride ion penetration [113]. The potential limitation of chloride penetration is of great importance. It also has the potential to reduce the carbon footprint in the atmosphere.

6.3. Sulfate attack

Sulfate attack is among the aspects that can influence the durability of foam concrete when subjected to sulfate-containing soil or water, resulting in structure softening and cracking [114]. There are three major cations associated with sulfate: sodium, magnesium, and calcium, all of which are more harmful to cement-based materials. Also, the sulfates associated with magnesium are more damaging than sodium. Also, both are more violent than sulfates associated with calcium.

Ettringite (Aft) is also more stable in sodium sulfate solution due to the formation of the monosulfate phase from Calcium Aluminum Hydrate (CAH) via ion exchange. Sodium sulfate attacks cement in two phases [115]. First, as shown in Eq. (3, the calcium hydroxide (CH) reacts with sodium sulfate and form gypsum. During the second stage of the attack, the formed gypsum from Eq. (3 and monosulfoaluminate (AFm) will interact to produce AFt; Eq. (4. AFt is a weak component of cementitious materials that lowers resistance to sulfate intrusion. Nevertheless, as soon as the CH depletes, gypsum formation will stop. As a result, once the AFm is used up, extra gypsum forms in the structure, and Aft formation ceases. The reaction between sodium sulfate and tricalcium aluminate (C_3A) forms AFt, as shown in Eq. (5 [116].

$$CH + N_2SH_{10} \rightarrow CSH_2 + 2NH + 8H \quad (3)$$

$$C_3A(CS)H_{12} + 2CSH_2 + 16H \rightarrow C_3A(CS)_3H_{32} \quad (4)$$

$$2C_3AH_6 + 3N_2SH_{10} \rightarrow C_3A(CS)_3H_{32} + 2AH_3 + 6NH + 5H \quad (5)$$

During sulfate attack, sulfate ions interact with the hydration products in cement, forming gypsum. This gypsum subsequently reacts with tricalcium aluminate (C_3A) present in the concrete to generate Aft, which induces significant internal stresses that can cause cracking [91].

Othman et al. [117] studied the durability through foamed concrete sulfate resistance. The research evaluated a period of 52 weeks after immersion sulfate resistance (5% sodium sulfate) of foam concrete specimens that contained processed spent bleaching earth (PSBE) as a partial cement replacement. This was done by investigating expansion, mass loss, and strength loss rate.

The results showed that using 30% of PSBE improved the sulfate resistance of foam concrete i.e., the specimens were more resistant when compared to conventional foamed concrete. The SEM images in Fig. 9 before immersion in 5% sodium sulfate revealed more pores in the FC than that of the specimen containing PSBE (PFC). This is due to the pozzolanic reactions between reactive silica (SiO_2) and portlandite released by cement hydration to form hexagonal plates of CSH responsible to the densification of the microstructure.

When the specimens of FC were immersed in the sodium sulfate solution, it was observed that ettringite needles were formed (Fig. 9). The strong peaks of calcium (Ca) and aluminum (Al) in the EDX patterns of FC confirmed the presence of ettringite. These strong peaks were accompanied by weak peaks of silicon (Si) and ferrite (Fe). It was reported that the presence of ettringite in a sulfate medium could lead to the expansion and deterioration of concrete specimens [114]. For this reason, many researchers [85,88,118–121] used SMCs such as SF, slag, and FA to prevent sulfate attacks in order to enhance the durability.

Bodur et al. [85] through durability tests, revealed that adding 0.5% basalt fibers (BF) and 30% attapulgite (ATP) significantly improved foam concrete resistance to sulfate attack ($MgSO_4$), even after prolonged exposure. The enhancement was attributed to ATP pozzolanic reactivity, which increased sulfate durability by producing a denser microstructure, decreasing permeability, and limiting the entry of hostile ions.

Slag foam concrete (SFC) made by partially substituting blast furnace slag (BFS) for OPC in percentages of 0, 30, 50, 70, and 100% to evaluate their resistance to different salts attack was investigated [121]. SFC outperformed normal foam concrete (NFC) in salt environments (Na_2SO_4, NaCl and their combination), with chloride reducing the negative impacts of sulfate on compressive strength. Since excessive replacement (50%) started to degrade performance, the ideal BFS replacement amount was determined to be 30%, providing the optimum resistance to salt erosion. Sulfate and chloride ions initially promoted

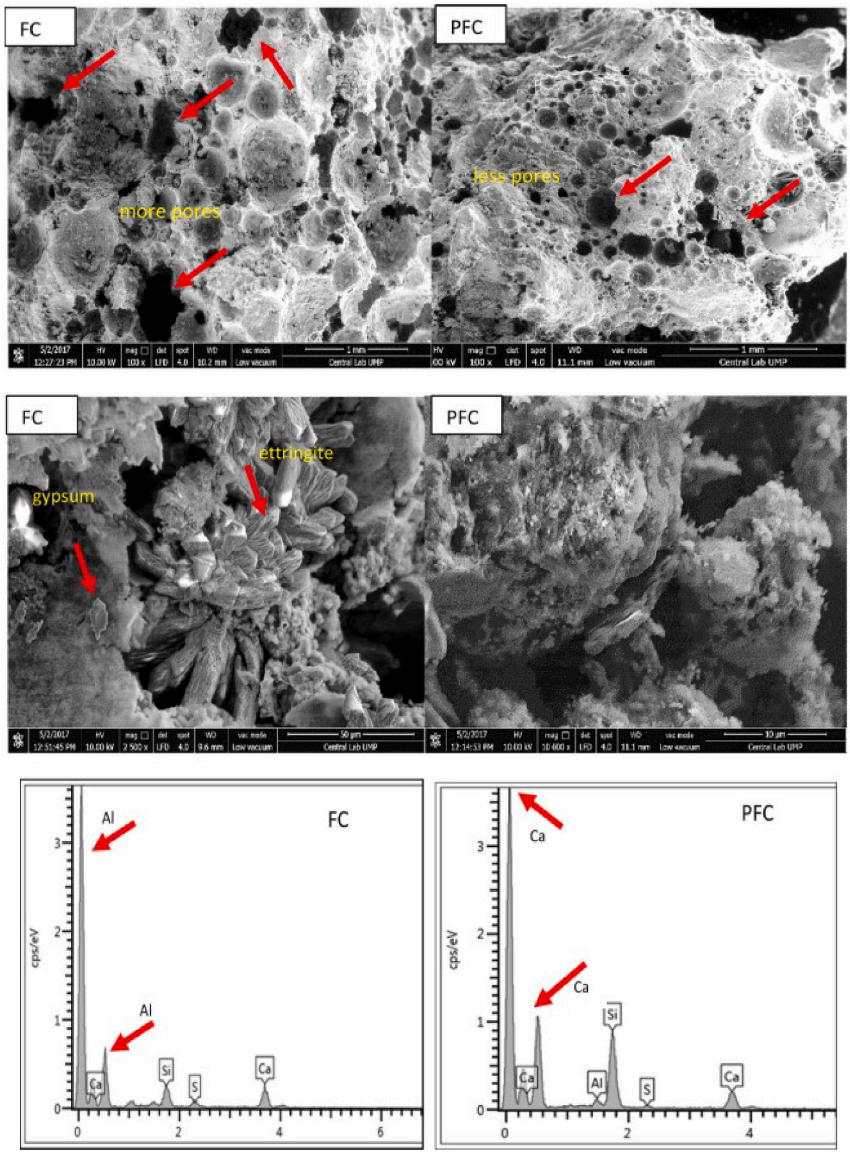

Fig. 9. SEM and EDX analyses of FC and PFC in 5% sodium sulfate; 52 weeks of immersion [109,117].

Aft production, filling in cracks and decreasing porosity. However, extended exposure caused Aft to expand and cause microstructural damage as shown in Fig. 10. Hydration studies showed that BFS-enhanced mixes had lower $Ca(OH)_2$ and more gel formation. It was found that substituting limestone with slag aggregate in GFC reduced the expansion to the sulfate due to the reduced porosity [67]

Chen et al. [122] investigated the resistance of foam concrete of a density of 900 kg/m^3 with different FA-to-cement (FA/C) ratios (0.2, 0.5, and 1) to 5, 10 and 15% Na_2SO_4 solution. They found that sulfate-immersed samples gained 3 to 5 times more mass than water-immersed ones, mainly within the first 7 days. Both the sulfate content and the FA/C ratio had an impact on this increase. Comparing sulfate exposure to conventional curing and water immersion, compressive strength increased; nevertheless, the sulfate-exposed samples exhibited greater brittle behavior. They had a high residual strength despite their brittleness, suggesting that they were resistant to sulfate attack.

The resistance of alkali-activated foam concrete (AAFC) mixes that contain FA (0, 25, 50%), ground blast furnace slag (GBFS), and pine cone powder (PCP, 0, 25, 50, 100%) to 10% $MgSO_4$ and 10% Na_2SO_4 attacks was investigated [123]. The compressive strength showed that 50% FA content significantly increased resistance to $MgSO_4$ and decreased strength loss because fewer calcium-rich phases (C-S-H) reacted with sulfates. By reducing the production of reactive sulfate compounds (Aft), replacing silica sand (SS) with PCP significantly improved resistance, particularly at 100% PCP. On the other hand, exposure to Na_2SO_4 increased strength, particularly in mixes rich in GBFS. The reference mix (0% FA and PCP) showed the greatest increases because of the continuous hydration and densification. The presence of GBFS produced more C-S-H gels, which were responsible for the resistance to Na_2SO_4. However, adding more FA decreased the strength improvement because FA has a lower reactivity than GBFS.

The performance under both sulfate types was impacted differentially by the PCP porous nature. It improved the internal water regulation, which helped decrease strength loss under $MgSO_4$, while boosting geopolymerization, and it increased strength gains under Na_2SO_4 at higher FA levels. The weight change study showed that because PCP reduces permeability, the reference mix lost the most weight under $MgSO_4$, whereas the 0% FA-50 % PCP mix lost the least. All of the mixes increased in weight in Na_2SO_4, but the 50% FA-50% PCP mix had the largest rise because of the synergistic densification effects.

The microstructural investigations showed that, particularly in

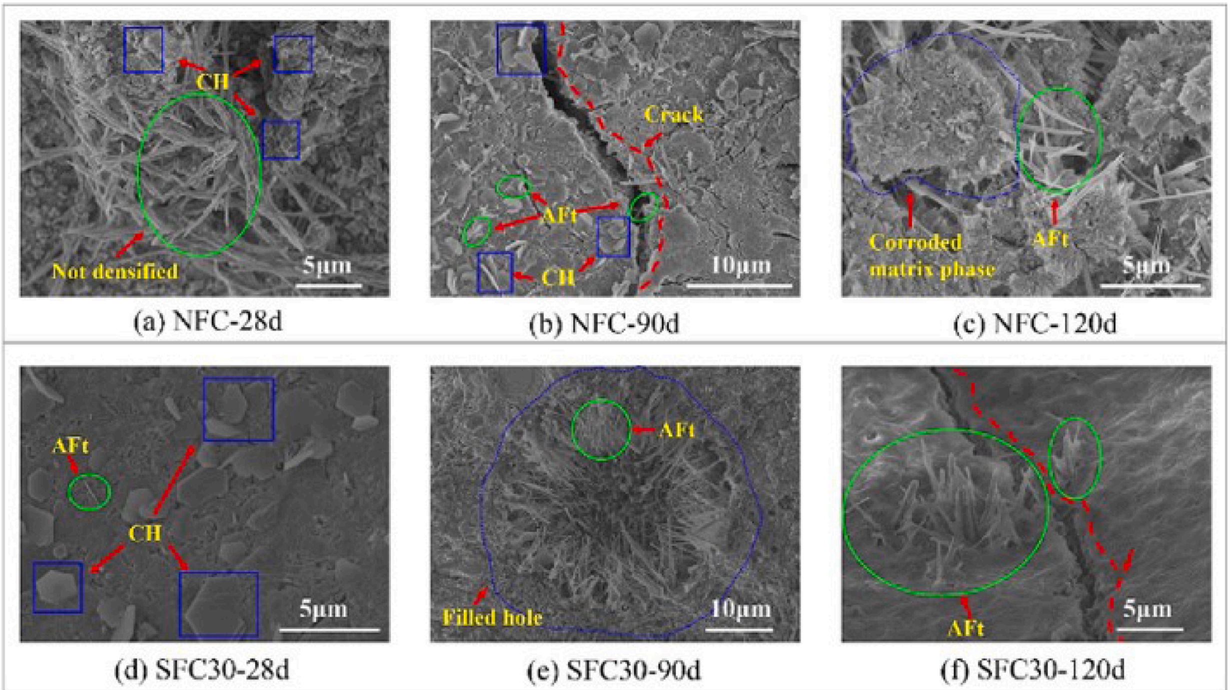

Fig. 10. SEM images of NFC and SFC after exposure to Na2SO_4 + NaCl [121].

combinations with a high calcium content, such as GBFS, exposure to $MgSO_4$ causes significant microstructural deterioration in AAFC, which is typified by extensive cracking, hollow structures, and increased porosity. Na_2SO_4, on the other hand, results in less serious damage. Its strength is initially increased by pore-filling by expansive products as ettringite and N-A-S-H, but its long-term durability decreases as a result of crack development and increasing porosity. By reducing the calcium concentration and encouraging the development of more stable phases like C-A-S-H, FA increases resistance to sulphates.

7. Conclusions

This paper presents an overview of the current understanding of the effects of SCMs on foam concretes. This has been shown to reduce the clinker factor in foam concrete engineering and industry. Salient conclusions arising from this literature review are summarized as follows.

- Foam concrete demands specialized workability tests. Due to its distinct composition, foam concrete requires unique testing methods such as the Marsh cone and mini-slump cone to accurately assess flow and consistency. Higher foam content reduces workability because of increased air voids and cohesiveness. Additives like fly ash, glass sand, and waste gypsum board improve flow by enhancing particle packing, whereas water-absorptive or irregular materials like SCBA and hemp fibers reduce it.
- Material composition critically influences thermal and shrinkage behavior. Foam concrete's physical performance particularly shrinkage, thermal conductivity, and microstructure is strongly governed by its constituent materials. The lack of coarse aggregates increases shrinkage, which can be reduced using additives like fly ash and recycled powders. Thermal conductivity is primarily driven by porosity, density, and moisture content, with SCMs refining pore structure and enhancing durability through pozzolanic action.
- Mechanical strength hinges on density, additives, and fiber reinforcement. The compressive, flexural, and tensile strengths of foam concrete are influenced by its density, mix design, and the inclusion of pozzolanic materials such as silica fume, fly ash, and metakaolin. Fiber additions such as polypropylene or basalt reduce brittleness and improve tensile performance, especially when aligned with optimized foaming and curing strategies.
- Durability is governed by pore structure and moisture resistance. Long-term durability is largely dictated by porosity, water absorption, and permeability, all of which are shaped by curing, density, and the use of SCMs. SCMs and fibers such as polypropylene enhance resistance to water and chloride ingress by refining the pore network. Additionally, SCMs help mitigate sulfate attack by densifying the matrix and restricting ion movement.
- Future research should optimize SCM combinations and real-world application. Studies should further explore the synergistic use of multiple SCMs to enhance performance and sustainability. Metakaolin, in particular, remains under-researched. To support broader adoption, foam concrete must be evaluated under aggressive environmental conditions and field-scale scenarios. Establishing standards, life-cycle assessments, and integrating digital tools for performance modeling will be essential for industry adoption.

CRediT authorship contribution statement

Alassane Compaore: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Jean-Yves N'Zy Kicoun Toure:** Writing – review & editing, Data curation, Conceptualization. **Desmond Edem Primus Klenam:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Abdallah Sarroney Merenga:** Writing – review & editing, Supervision, Project administration, Data curation, Conceptualization. **Tabiri Kwayie Asumadu:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **John David Obayemi:** Writing – review & editing, Data curation, Conceptualization. **Nima Rahbar:** Writing – review & editing, Supervision, Conceptualization. **Charles Migwi:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Winston Oluwole Soboyejo:** Writing – review & editing, Supervision, Resources, Project administration, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] (UNEP) United Nations Environment Programme, 2020 Global Status Report For Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector, 2020.
[2] P.K. Mehta, P.A. Claisse, and T.R. Naik, "Sustainable Cements and Concrete for the Climate Change Era - A Review," 2010.
[3] T. Tazmeen, F.Q. Mir, Sustainability through materials: a review of green options in construction, Results Surf. Interfaces 14 (2024) 100206, https://doi.org/10.1016/j.rsurfi.2024.100206.
[4] O. Gencel, T. Bilir, Z. Bademler, T. Ozbakkaloglu, A Detailed Review on Foam Concrete Composites: ingredients, Properties, and Microstructure, Appl. Sci. 12 (11) (2022), https://doi.org/10.3390/app12115752.
[5] L. Ricciotti, A. Occhicone, A. Petrillo, C. Ferone, R. Cioffi, G. Roviello, Geopolymer-based hybrid foams: lightweight materials from a sustainable production process, J. Clean. Prod. 250 (2020) 119588, https://doi.org/10.1016/j.jclepro.2019.119588.
[6] Y.H.M. Amran, N. Farzadnia, A.A.A. Ali, Properties and applications of foamed concrete; A review, Constr. Build. Mater. 101 (2015) 990–1005, https://doi.org/10.1016/j.conbuildmat.2015.10.112.
[7] O.Y. Bayraktar, et al., Basalt fiber reinforced foam concrete with marble waste and calcium aluminate cement, Struct. Concr. 24 (1) (2023) 1152–1178, https://doi.org/10.1002/suco.202200142.
[8] J. Jiang, Z. Lu, Y. Niu, J. Li, Y. Zhang, Investigation of the properties of high-porosity cement foams based on ternary Portland cement-metakaolin-silica fume blends, Constr. Build. Mater. 107 (2016) 181–190, https://doi.org/10.1016/j.conbuildmat.2015.12.190.
[9] M. Aswathy, Experimental study on light weight foamed concrete, Int. J. Civ. Eng. Technol. 8 (8) (2017) 1404–1412.
[10] G. Krishnan, K.B. Anand, Industrial waste utilization for foam concrete, in: IOP Conference Series: Materials Science and Engineering, 2018 012062, https://doi.org/10.1088/1757-899X/310/1/012062.
[11] D. Falliano, et al., Influence of biochar additions on the fracture behavior of foamed concrete, Frat. ed Integrita Strutt. 14 (51) (2020) 189–198, https://doi.org/10.3221/IGF-ESIS.51.15.
[12] J. Sarazin, et al., Flame resistance of geopolymer foam coatings for the fire protection of steel, Compos. Part B Eng. 222 (2021) 109045, https://doi.org/10.1016/j.compositesb.2021.109045.
[13] H. Yuan, et al., Drying shrinkage, durability and microstructure of foamed concrete containing high volume lime mud-fly ash, Constr. Build. Mater. 327 (12) (2022) 126990, https://doi.org/10.1016/j.conbuildmat.2022.126990.
[14] H.S. Gökçe, D. Hatungimana, K. Ramyar, Effect of fly ash and silica fume on hardened properties of foam concrete, Constr. Build. Mater. 194 (2019) 1–11, https://doi.org/10.1016/j.conbuildmat.2018.11.036.
[15] A. Vishavkarma, H.Kizhakkumodom Venkatanarayanan, Assessment of pore structure of foam concrete containing slag for improved durability performance in reinforced concrete applications, J. Build. Eng. 86 (2024) 108939, https://doi.org/10.1016/j.jobe.2024.108939.
[16] A. Benli, M. Karataş, E. Gurses, Effect of sea water and MgSO4 solution on the mechanical properties and durability of self-compacting mortars with fly ash/silica fume, Constr. Build. Mater. 146 (2017) 464–474, https://doi.org/10.1016/j.conbuildmat.2017.04.108.
[17] F. Koksal, E.T. Kocabeyoglu, O. Gencel, A. Benli, The effects of high temperature and cooling regimes on the mechanical and durability properties of basalt fiber reinforced mortars with silica fume, Cem. Concr. Compos. 121 (2021) 104107, https://doi.org/10.1016/j.cemconcomp.2021.104107.
[18] M.U. Yılmazoğlu, H.O. Kara, A. Benli, A.R. Demirkıran, O.Y. Bayraktar, G. Kaplan, Sustainable alkali-activated foam concrete with pumice aggregate: effects of clinoptilolite zeolite and fly ash on strength, durability, and thermal performance, Constr. Build. Mater. 464 (2025) 140160, https://doi.org/10.1016/j.conbuildmat.2025.140160.
[19] S.S. Sahu, I.S.R. Gandhi, S. Khwairakpam, I. Siva, R. Gandhi, S. Khwairakpam, State-of-the-Art Review on the Characteristics of Surfactants and Foam from Foam Concrete Perspective, J. Inst. Eng. Ser. A 99 (2) (2018) 391–405, https://doi.org/10.1007/s40030-018-0288-5.
[20] N.P. Tran, T.N. Nguyen, T.D. Ngo, P.K. Le, T.A. Le, Strategic progress in foam stabilisation towards high-performance foam concrete for building sustainability: a state-of-the-art review, J. Clean. Prod. 375 (2022) 133939, https://doi.org/10.1016/j.jclepro.2022.133939.
[21] H. Huang, Q. Yuan, D. Deng, J. Peng, Y. Huang, Effects of chemical and mineral admixtures on the foam indexes of cement-based materials, Case Stud. Constr. Mater. 11 (2019) 1–16, https://doi.org/10.1016/j.cscm.2019.e00232.
[22] Z. Zhang, J.L. Provis, A. Reid, H. Wang, Geopolymer foam concrete: an emerging material for sustainable construction, Constr. Build. Mater. 56 (2014) 113–127, https://doi.org/10.1016/j.conbuildmat.2014.01.081.
[23] E. Papa, et al., Porosity and insulating properties of silica-fume based foams, Energy Build 131 (2016) 223–232, https://doi.org/10.1016/j.enbuild.2016.09.031.
[24] Z. Zhang, H. Wang, The pore characteristics of geopolymer foam concrete and their impact on the compressive strength and modulus, Front. Mater. 3 (38) (2016) 1–10, https://doi.org/10.3389/fmats.2016.00038.
[25] N.B. Singh, Foamed geopolymer concrete, in: *Materials Today: Proceedings*, Elsevier Ltd, 2018, pp. 15243–15252, https://doi.org/10.1016/j.matpr.2018.05.002.
[26] Y. Fu, X. Wang, L. Wang, Y. Li, Foam Concrete: a State-of-the-Art and State-of-the-Practice Review, Adv. Mater. Sci. Eng. 2020 (2020) 6153602, https://doi.org/10.1155/2020/6153602.
[27] G. Zhou, R.K.L. Su, A Review on Durability of Foam Concrete, Buildings 13 (7) (2023), https://doi.org/10.3390/buildings13071880.
[28] G. Samson, A. Phelipot-Mardelé, C. Lanos, A review of thermomechanical properties of lightweight concrete, Mag. Concr. Res. 69 (4) (2017) 201–216, https://doi.org/10.1680/jmacr.16.00324.
[29] A. Hajimohammadi, T. Ngo, P. Mendis, Enhancing the strength of pre-made foams for foam concrete applications, Cem. Concr. Compos. 87 (2018) 164–171, https://doi.org/10.1016/j.cemconcomp.2017.12.014.
[30] L. Korat, V. Ducman, The influence of the stabilizing agent SDS on porosity development in alkali-activated fly-ash based foams, Cem. Concr. Compos. 80 (2017) 168–174, https://doi.org/10.1016/j.cemconcomp.2017.03.010.
[31] P. Hlaváček, V. Šmilauer, F. Škvára, L. Kopecký, R. Šulc, Inorganic foams made from alkali-activated fly ash: mechanical, chemical and physical properties, J. Eur. Ceram. Soc. 35 (2) (2015) 703–709, https://doi.org/10.1016/j.jeurceramsoc.2014.08.024.
[32] G. Masi, W.D.A. Rickard, L. Vickers, M.C. Bignozzi, A. Van Riessen, A comparison between different foaming methods for the synthesis of light weight geopolymers, Ceram. Int. 40 (9) (2014) 13891–13902, https://doi.org/10.1016/j.ceramint.2014.05.108. PART A.
[33] C. Bing, W. Zhen, L. Ning, Experimental research on properties of high strength foamed concrete, J. Mater. Civ. Eng. 22 (5) (2012) 321–329.
[34] C.C. Bayar, T.O. Onur, G.U. Kaya, N. Kunduraci, Imaging of foam concrete air bubbles with an alternative method of combined digital holographic microscopy, J. Mater. Sci. 59 (20) (2024) 8706–8720, https://doi.org/10.1007/s10853-024-09726-x.
[35] Y. Liu, Z. Zhao, M.N. Amin, B. Ahmed, S.U. Arifeen, F. Althoey, Foam concrete for lightweight construction applications : a comprehensive review of the research development and material characteristics, Rev. Adv. Mater. Sci. 63 (2024) 20240022.
[36] S. Wei, C. Yiqiang, Z. Yunsheng, M.R. Jones, Characterization and simulation of microstructure and thermal properties of foamed concrete, Constr. Build. Mater. 47 (2013) 1278–1291, https://doi.org/10.1016/j.conbuildmat.2013.06.027.
[37] J. Wu, Z. Zhang, Y. Zhang, D. Li, Preparation and characterization of ultra-lightweight foamed geopolymer (UFG) based on fly ash-metakaolin blends, Constr. Build. Mater. 168 (2018) 771–779, https://doi.org/10.1016/j.conbuildmat.2018.02.097.
[38] K. Ramamurthy, E.K.K. Nambiar, G.I.S. Ranjani, A classification of studies on properties of foam concrete, Cem. Concr. Compos. 31 (2009) 388–396, https://doi.org/10.1016/j.cemconcomp.2009.04.006.
[39] A. Just, B. Middendorf, Microstructure of high-strength foam concrete, Mater. Charact. 60 (7) (2009) 741–748, https://doi.org/10.1016/j.matchar.2008.12.011.
[40] H. Zhou, X. Zhang, X. Wang, H. Zhang, T. Song, Improving energy absorption capacity of foam concrete with gradient and layered architecture, Constr. Build. Mater. 319 (2022) 126140, https://doi.org/10.1016/j.conbuildmat.2021.126140.
[41] S. Feng, Y. Zhou, Y. Wang, M. Lei, Experimental research on the dynamic mechanical properties and damage characteristics of lightweight foamed concrete under impact loading, Int. J. Impact Eng. 140 (2020) 103558, https://doi.org/10.1016/j.ijimpeng.2020.103558.
[42] Y. Hao, H. Wang, L. Qin, H. Sun, Y. Zhao, C. kelehan, Experimental and numerical study on seismic performance of prefabricated new fly ash foam concrete structure, Soil Dyn. Earthq. Eng. 178 (2024) 108462, https://doi.org/10.1016/j.soildyn.2024.108462.
[43] N. Deepak, H. Thiagu, S. Manivel, Study on strength of Metakaolin based foamed concrete under different elevated temperature, ARPN J. Eng. Appl. Sci. 14 (17) (2019) 2980–2986.
[44] P. Krishna Kumar, K. Chinnaraju, Comparative Experimental Investigation on Foam Concrete With Polypropylene Fiber and Carbon Fiber, Rom. J. Mater. 52 (3) (2022) 265–277.
[45] A.S. Tarasov, E.P. Kearsley, A.S. Kolomatskiy, H.F. Mostert, Heat evolution due to cement hydration in foamed concrete, Mag. Concr. Res. 62 (12) (2010) 895–906, https://doi.org/10.1680/macr.2010.62.12.895.
[46] P.J. Tikalsky, J. Pospisil, W. MacDonald, A method for assessment of the freeze–thaw resistance of preformed foam cellular concrete. Cement and Concrete Research, Cem. Concr. Res. 34 (5) (2004) 889–893, https://doi.org/10.1016/j.cemconres.2003.11.005.

[47] ASTM C359-13, Standard Test Method For Early Stiffening of Hydraulic Cement, ASTM Int. West Conshohocken, Pennsylvania, 2013.
[48] E.K. Kunhanandan Nambiar, K. Ramamurthy, Fresh State Characteristics of Foam Concrete, J. Mater. Civ. Eng. 20 (2) (2008) 111–117, https://doi.org/10.1061/(asce)0899-1561(2008)20:2(111).
[49] O. Gencel, et al., Lightweight foam concrete containing expanded perlite and glass sand: physico-mechanical, durability, and insulation properties, Constr. Build. Mater. 320 (2022) 126187, https://doi.org/10.1016/j.conbuildmat.2021.126187.
[50] O. Gencel, et al., Characteristics of hemp fibre reinforced foam concretes with fly ash and Taguchi optimization, Constr. Build. Mater. 294 (2021) 123607, https://doi.org/10.1016/j.conbuildmat.2021.123607.
[51] ASTM C1749-17, Standard Guide for Measurement of the Rheological Properties of Hydraulic Cementious Paste Using a Rotational Rheometer1, ASTM Int. West Conshohocken, Pennsylvania (2017) 1–5.
[52] A. Bagheri, S.A. Samea, Parameters Influencing the Stability of Foamed Concrete, J. Mater. Civ. Eng. 30 (6) (2018) 04018091, https://doi.org/10.1061/(asce)mt.1943-5533.0002290.
[53] A. Raj, D. Sathyan, K.M. Mini, Physical and functional characteristics of foam concrete: a review, Constr. Build. Mater. 221 (2019) 787–799, https://doi.org/10.1016/j.conbuildmat.2019.06.052.
[54] A.S. Krishna, R. Siempu, G.A.V.S.S. Kumar, Study on the fresh and hardened properties of foam concrete incorporating fly ash, in: Materials Today: Proceedings, Elsevier Ltd, 2021, pp. 639–8644, https://doi.org/10.1016/j.matpr.2021.03.599.
[55] E.K.K. Nambiar, K. Ramamurthy, Influence of filler type on the properties of foam concrete, Cem. Concr. Compos. 28 (5) (2006) 475–480, https://doi.org/10.1016/j.cemconcomp.2005.12.001.
[56] S. Feng, Y. Gao, H. Xiao, C. Xue, Influence of fibers and bubble structure on thermal conductivity and mechanical performances of foam concrete, Constr. Build. Mater. 445 (2024) 137956, https://doi.org/10.1016/j.conbuildmat.2024.137956.
[57] S.A. Khawaja, U. Javed, T. Zafar, M. Riaz, M.S. Zafar, M.K. Khan, Eco-friendly incorporation of sugarcane bagasse ash as partial replacement of sand in foam concrete, Clean. Eng. Technol. 4 (2021) 100164, https://doi.org/10.1016/j.clet.2021.100164.
[58] A.M. Maglad, M.A.O. Mydin, R.C. Kaze, I.S. Abbood, B.A. Tayeh, Synergistic effect of waste gypsum plasterboard and fly ash as partial cement replacement on fresh-state, microstructural, mechanical and transport properties of foamed concrete, Constr. Build. Mater. 463 (2025) 140079, https://doi.org/10.1016/j.conbuildmat.2025.140079.
[59] M.K.I. Kabbo, et al., Experimental assessment and machine learning quantification of structural eco-cellular lightweight concrete incorporating waste marble powder and silica fume, J. Build. Eng. 105 (2025) 112557.
[60] D. Zhang, W. Hao, Q. Yang, Experimental Study on the Application of Recycled Concrete Waste Powder in Alkali-Activated Foamed Concrete, Materials (Basel) 16 (17) (2023) 1–16, https://doi.org/10.3390/ma16175728.
[61] E.K.K. Nambiar, K. Ramamurthy, Shrinkage Behavior of Foam Concrete, J. Mater. Civ. Eng. ASCE 21 (11) (2009) 631–636, https://doi.org/10.1061/(ASCE)0899-1561(2009)21.
[62] O. Gencel, A. Benlib, O.Y. Bayraktarc, G. Kapland, M. Sutcue, W.A.T. Elabadef, 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. 291 (2021) 123374.
[63] D. Yang, M. Liu, Z. Zhang, P. Yao, Z. Ma, Properties and modification of sustainable foam concrete including eco-friendly recycled powder from concrete waste, in: Case Studies in Construction Materials, 16, Elsevier Ltd, 2022 e00826, https://doi.org/10.1016/j.cscm.2021.e00826.
[64] H. Wu, C. Liang, J. Xiao, J. Xu, Z. Ma, Early-age behavior and mechanical properties of cement-based materials with various types and fineness of recycled powder, Struct. Concr. 23 (2) (2022) 1253–1272, https://doi.org/10.1002/suco.202000834.
[65] H. Zhang, X. Qi, C. Ma, J. Wu, Y. Bi, Effect Analysis of Soil Type and Silt Content on Silt-Based Foamed Concrete with Different Density, Materials 13 (3866) (2020) 2–14, https://doi.org/10.3390/ma13173866.
[66] X. Li, W. Fu, P. Wang, J. Zhou, Z. Hu, Z. Guo, Enhancing foamed concrete performance with pre-wetted ceramsite: mitigating early cracking, shrinkage, and improving interfacial transition zone properties, Constr. Build. Mater. 458 (2025) 139509.
[67] A. Ahıskalı, M. Ahıskalı, O.Y. Bayraktar, G. okhan Kaplan, J. Assaad, Mechanical and durability properties of polymer fiber reinforced one-part foam geopolymer concrete: a sustainable strategy for the recycling of waste steel slag aggregate and fly ash, Constr. Build. Mater. 440 (2024) 137492.
[68] M. Cong, C. Bing, Properties of a foamed concrete with soil as filler, Constr. Build. Mater. 76 (2015) 61–69, https://doi.org/10.1016/j.conbuildmat.2014.11.066.
[69] J. Gołaszewski, et al., Effect of Foaming Agent, Binder and Density on the Compressive Strength and Thermal Conductivity of Ultra-Light Foam Concrete, Buildings 12 (8) (2022) 1176, https://doi.org/10.3390/buildings12081176.
[70] X. Zhao, et al., Properties of foamed mortar prepared with granulated blast-furnace slag, Materials (Basel) 8 (2) (2015) 462–473, https://doi.org/10.3390/ma8020462.
[71] A.A. Hilal, T.H. Nicholas, R.D. Andrew, The Use of Additives to Enhance Properties of Pre- Formed Foamed Concrete, Int. J. Eng. Technol. 7 (4) (2015) 286–293, https://doi.org/10.7763/ijet.2015.v7.806.
[72] M.R. Jones, A. McCarthy, Behaviour and Assessment of Foamed Concrete for Construction Applications, in: Proceedings of the International Conference on the Use of Foamed Concrete in Construction, 2005, pp. 61–88.
[73] F. Batool, V. Bindiganavile, Air-void size distribution of cement based foam and its effect on thermal conductivity, Constr. Build. Mater. 149 (2017) 17–28, https://doi.org/10.1016/j.conbuildmat.2017.05.114.
[74] A. Compaoré, et al., Preparation and characterization of foamed concrete using a foaming agent and local mineral resources from Burkina Faso, Results Mater 17 (17) (2023) 100365, https://doi.org/10.1016/j.rinma.2023.100365.
[75] E. Bartenjeva, The effect of mineral additives on foam concrete porosity, in: IOP Conf. Series: Materials Science and Engineering, 2020, p. 962, https://doi.org/10.1088/1757-899X/962/2/022023.
[76] N. Song, Z. Li, S. Wang, G. Li, Biochar as internal curing material to prepare foamed concrete, Constr. Build. Mater. 377 (February) (2023) 131030.
[77] X. Zhang, et al., Experimental study on the physico-mechanical properties and microstructure of foam concrete mixed with coal gangue, Constr. Build. Mater. 359 (2022) 12942, https://doi.org/10.1016/j.conbuildmat.2022.129428.
[78] A.A. Hilal, T.H. Nicholas, D.A. Robert, On void structure and strength of foamed concrete made without/with additives, Constr. Build. Mater. 85 (2015) 157–164, https://doi.org/10.1016/j.conbuildmat.2015.03.093.
[79] E.K.K. Nambiar, K. Ramamurthy, Models relating mixture composition to the density and strength of foam concrete using response surface methodology, Cem. Concr. Compos. 28 (2006) 752–760, https://doi.org/10.1016/j.cemconcomp.2006.06.001.
[80] A.A. Hilal, N.H. Thorn, A.R. Dawson, Failure mechanism of foamed concrete made with/without additives and lightweight aggregate, J. Adv. Concr. Technol. 14 (9) (2016) 511–520, https://doi.org/10.3151/jact.14.511.
[81] O. Gencel, et al., Basalt fiber-reinforced foam concrete containing silica fume: an experimental study, Constr. Build. Mater. 326 (2022) 126861, https://doi.org/10.1016/j.conbuildmat.2022.126861.
[82] M.S. Manharawy, A.A. Mahmoud, O.O. El-Mahdy, M.H. El-Diasity, Experimental and numerical investigation of lightweight foamed reinforced concrete deep beams with steel fibers, Eng. Struct. 260 (2022) 114202, https://doi.org/10.1016/j.engstruct.2022.114202.
[83] Y.H. Mugahed Amran, et al., Performance properties of structural fibred-foamed concrete, Results Eng 5 (2020) 11–13, https://doi.org/10.1016/j.rineng.2019.100092.
[84] G.Pavan Kumar, A. Ravitheja, C.Madhu Anjaneyulu, Mechanical and durability properties of hybrid fiber reactive powder concrete, Mater. Today Proc. 46 (2021) 16–20, https://doi.org/10.1016/j.matpr.2020.03.647.
[85] B. Bodur, A. Benli, O.Y. Bayraktar, H.G. Alcan, G. Kaplan, A.C. Aydın, Impact of attapulgite and basalt fiber additions on the performance of pumice-based foam concrete: mechanical, thermal, and durability properties, Arch. Civ. Mech. Eng. 25 (2) (2025) 1–25, https://doi.org/10.1007/s43452-025-01128-3.
[86] X. Wang, L. Liu, H. Zhou, T. Song, Q. Qiao, H. Zhang, Improving the compressive performance of foam concrete with ceramsite : experimental and meso -scale numerical investigation, Mater. Des. 208 (2021) 109938, https://doi.org/10.1016/j.matdes.2021.109938.
[87] N. Vinith Kumar, C. Arunkumar, S.Srinivasa Senthil, Experimental Study on Mechanical and Thermal Behavior of Foamed Concrete, in: Materials Today: Proceedings, 2018, pp. 8753–8760, https://doi.org/10.1016/j.matpr.2017.12.302.
[88] O.Y. Bayraktar, A. Ahıskalı, M. Ahıskalı, F. Ekşioğlu, G. Kaplan, J. Assaad, Feasibility of foam concrete using recycled brick and roof tile fine aggregates, Eur. J. Environ. Civ. Eng. 8189 (2024), https://doi.org/10.1080/19648189.2024.2407868.
[89] E. Rommel, L. Prasetyol, Y. Rusdianto, R. Karimah, A.S. R, C.S.A. N, The insulation properties of foam concrete with the use of foam-agent and fly-ash, in: IPO Conference series: Materials Science and engineering, 2020 012013, https://doi.org/10.1088/1757-899X/821/1/012013.
[90] T. Yao, et al., Experimental research on the preparation and properties of foamed concrete using recycled waste concrete powder, Constr. Build. Mater. 407 (2023) 133370, https://doi.org/10.1016/j.conbuildmat.2023.133370.
[91] O. Gencel, et al., Influence of bottom ash and polypropylene fibers on the physico-mechanical, durability and thermal performance of foam concrete: an experimental investigation, Constr. Build. Mater. 306 (June) (2021) 124887, https://doi.org/10.1016/j.conbuildmat.2021.124887.
[92] D. Huiskes, A. Keulen, Q. Yu, H. Brouwers, Design and performance evaluation of ultra-lightweight geopolymer concrete, Mater. Des. 89 (2016) 516–526, https://doi.org/10.1016/j.matdes.2015.09.167.
[93] D. Falliano, D. De Domenico, G. Ricciardi, E. Gugliandolo, Experimental investigation on the compressive strength of foamed concrete: effect of curing conditions, cement type, foaming agent and dry density, Constr. Build. Mater. 165 (2018) 735–749, https://doi.org/10.1016/j.conbuildmat.2017.12.241.
[94] R. Kumar, R. Lakhani, and P. Tomar, "A simple novel mix design method and properties assessment of foamed concretes with limestone slurry waste," 2018. doi: 10.1016/j.jclepro.2017.10.073.
[95] O. Gencel, et al., Basalt fiber-reinforced foam concrete containing silica fume: an experimental study, Constr. Build. Mater. 326 (2022) 126861, https://doi.org/10.1016/j.conbuildmat.2022.126861.
[96] Z.M. Jaini, R.H.M. Rum, K.H. Boon, Strength and fracture energy of foamed concrete incorporating rice husk ash and polypropylene mega-mesh 55, IOP Conf. Ser. Mater. Sci. Eng. 248 (1) (2017) 012005, https://doi.org/10.1088/1757-899X/248/1/012005.
[97] J. Li, Y. Yu, T. Kim, A. Hajimohammadi, Unveiling the underlying mechanisms of tensile behaviour enhancement in fibre reinforced foam concrete, Constr. Build.

Mater. 398 (2023) 132509, https://doi.org/10.1016/j.conbuildmat.2023.132509.
[98] M.A.O. Mydin, et al., Thermal conductivity, microstructure and hardened characteristics of foamed concrete composite reinforced with raffia fiber, J. Mater. Res. Technol. 26 (2023) 850–864, https://doi.org/10.1016/j.jmrt.2023.07.225.
[99] N. Suksawang, S. Wtaife, A. Alsabbagh, Evaluation of elastic modulus of fiber-reinforced concrete, ACI Mater. J. 115 (2) (2018) 239–249, https://doi.org/10.14359/51701920.
[100] O.Y. Bayraktar, G. Kaplan, O. Gencel, A. Benli, M. Sutcu, Physico-mechanical, durability and thermal properties of basalt fiber reinforced foamed concrete containing waste marble powder and slag, Constr. Build. Mater. 288 (2021) 123128.
[101] T. Luo, et al., Reinforcing pore structure and ITZ of foam concrete enabled by DNA self-assembled CNTs networks, Case Stud. Constr. Mater. 22 (2025) e04748, https://doi.org/10.1016/j.cscm.2025.e04748.
[102] K. Nambiar, E.K.K. & Ramamurthy, Sorption characteristics of foam concrete, Cem. Concr. Res. 37 (9) (2007) 1341–1347, https://doi.org/10.1016/j.cemconres.2007.05.010.
[103] A. Baranova, V. Bygajchuk, Investigation of water absorption of non-autoclaved foam concretes based on microsilica, I O P Conf. Ser. Mater. Sci. Eng. 880 (2020) 012003, https://doi.org/10.1088/1757-899X/880/1/012003.
[104] P. Shawnim, F. Mohammad, Porosity, Permeability and Microstructure of Foamed Concrete through SEM Images, J. Civ. Eng. Sci. Technol. 10 (1) (2019) 22–33, https://doi.org/10.33736/jcest.1434.2019.
[105] L. Chaofeng, C. Zhedong, W. Huixia, X. Jianzhuang, Z. Yuming, M. Zhiming, Chloride transport and induced steel corrosion in recycled aggregate concrete: a review, Constr. Build. Mater. 282 (2021) 122547, https://doi.org/10.1016/j.conbuildmat.2021.122547.
[106] A. Bagheri, M.M. Rastegar, Investigation of passive layer formation on steel rebars in foamed concrete, Mater. Corros. 70 (7) (2019) 1252–1261, https://doi.org/10.1002/maco.201810663.
[107] M.M. Rastegar, A. Bagheri, Effect of foam volume on penetration parameters of foamed concrete, Mag. Concr. Res. 74 (19) (2022) 989–998, https://doi.org/10.1680/jmacr.21.00247.
[108] M. Wasim, T.Duc Ngo, D. Law, Durability performance of reinforced waste-based geopolymer foam concrete under exposure to various corrosive environments, Case Stud. Constr. Mater. 15 (2021) e00703, https://doi.org/10.1016/j.cscm.2021.e00703.
[109] R. Othman, et al., Compressive strength and durability of foamed concrete incorporating Processed Spent Bleaching Earth, Arch. Civ. Eng. 68 (2) (2022) 627–643, https://doi.org/10.24425/ace.2022.140663.
[110] L. Tang, L. Nilsson, P.A.M. Basheer, in: T, Francids (Eds.), Resistance of Concrete to Chloride Ingress; Testing Ingress Modelling, Taylor & Francis, 2011.
[111] O. Sengul, M.A. Tasdemir, Compressive Strength and Rapid Chloride Permeability of Concretes with Ground Fly Ash and Slag, J. Civ. Eng. 21 (9) (2009) 494–501, https://doi.org/10.1061/(asce)0899-1561(2009)21:9(494).
[112] O.H. Li, et al., Evaluation of the effect of silica fume on amorphous fly ash geopolymers exposed to elevated temperature, Magnetochemistry 7 (1) (2021) 1–14, https://doi.org/10.3390/magnetochemistry7010009.
[113] P. Sudha, R. Selvaraj, T. Palanisamy, Intensification of calcined clay as a pozzolanic material in cement mortar, Int. J. Appl. Eng. Res. 10 (15) (2015) 35640–35644.
[114] T. Drimalas, Laboratory And Field Evaluations Of External Sulfate Attack, The University of Texas at Austin, 2007 [Online]. Available, http://hdl.handle.net/2152/3569.
[115] R.P. Jaya, B.H. Abu Bakar, M.A. Megat Johari, M.H. Wan Ibrahim, M.R. Hainin, D.S. Jayanti, Strength and microstructure analysis of concrete containing rice husk ash under seawater attack by wetting and drying cycles, Adv. Cem. Res. 26 (3) (2014) 145–154, https://doi.org/10.1680/adcr.13.00010.
[116] W.H.R.S. Dayarathne, G.S. Galappaththi, K.E.S. Perera, S.M.A. Nanayakkara, Evaluation of the Potential for Delayed Ettringite Formation in Concrete, in: 19th ERU symposium, National Engineering Conference 2013, University of Moratuwa, Sri Lanka, 2013, pp. 59–66.
[117] Rokiah Othman, et al., Evaluation of the sulphate resistance of foamed concrete containing processed spent bleaching earth, Eur. J. Environ. Civ. Eng. 26 (8) (2022) 3632–3647, https://doi.org/10.1080/19648189.2020.1809526.
[118] M.R. Karim, M.M. Hossain, M.N.N. Khan, M.F.M. Zain, M. Jamil, F.C. Lai, On the utilization of pozzolanic wastes as an alternative resource of cement, Materials 7 (12) (2014) 7809–7827, https://doi.org/10.3390/ma7127809.
[119] H. Paiva, A. Velosa, P. Cachim, V.M. Ferreira, Effect of pozzolans with different physical and chemical characteristics on concrete properties, Mater. Construcción 66 (322) (2016), https://doi.org/10.3989/mc.2016.01815 p. e083.
[120] S. Barbhuiya, D. Kumala, Behaviour of a sustainable concrete in acidic environment, Sustainability 9 (9) (2017) 1556, https://doi.org/10.3390/su9091556.
[121] L. Chen, X. Chen, L. Wang, Y. Ning, T. Ji, Compressive strength, pore structure, and hydration products of slag foam concrete under sulfate and chloride environment, Constr. Build. Mater. 394 (2023) 132141, https://doi.org/10.1016/j.conbuildmat.2023.132141.
[122] Y. gui Chen, L. lei Guan, S. yi Zhu, W. jia Chen, Foamed concrete containing fly ash: properties and application to backfilling, Constr. Build. Mater. 273 (2021), https://doi.org/10.1016/j.conbuildmat.2020.121685.
[123] O.Y. Bayraktar, et al., Sustainable foam concrete development: enhancing durability and performance through pine cone powder and fly ash incorporation in alkali-activated geopolymers, Constr. Build. Mater. 457 (2024) 139422.