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Review

A Detailed Review on Foam Concrete Composites: Ingredients, Properties, and Microstructure

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Abstract: With the development of new cement-based raw materials, foaming agents and fillers used for special applications of foam concrete, the use of foam concretes has become widespread. Foam concrete is a type of concrete that stands out with its lightness, waste potential, controlled low strength, thermal insulation, acoustics performance, and durability. The knowledge base is still developing for this particular building material. This article describes in detail the fresh, hardened, and physical properties of foam concrete. The properties of materials such as cement, aggregate, foam, and fiber used in foam concrete production are explained and their effects on microstructure are discussed. In addition, physical properties, such as fresh state properties, fresh state and consistency, stability, workability, drying shrinkage, air void system, and water absorption, as well as strength and durability properties are emphasized. The main findings of the presented study are to show the current level of the cement-based foam concretes and their shortcomings, which needs more investigations. The effect of fibers on the characteristics of foam concrete and acoustic characteristic of foam concretes are seen as the main topics to be focused on in the studies.

Keywords: foam concrete; physico-mechanical properties; mixture design; thermal conductivity; microstructure

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1. Introduction

Foam concrete is a type of concrete that is produced by locking air voids in the mortar with the help of a suitable foaming agent and is classified as lightweight concrete. It has low self-weight, minimum aggregate consumption (no coarse aggregate is used), high fluidity, controlled low strength and thermal insulation [1]. The properties of foam concrete are affected by the production method and the materials used. Unlike other porous lightweight concrete, prefabricated foams with foaming agents are added to fresh cement paste and mortar. The air pores brought by the foams constitute 10–90% by volume of the hardened body. This porous structure forms the basis of the mechanical properties, thermal conductivity, acoustic and durability properties of foam concrete [2]. One of the advantages of foam concrete is its weight reduction (up to 80%) compared to conventional concrete [3]. The air bubbles are evenly distributed in the foam concrete body. The pore structure may be affected during the mixing, transportation and placement of fresh concrete, so it should have fixed walls. Air bubbles range in size from approximately 0.1 to 1 mm [4]. The density of foam concrete is mainly affected by the amount of foam and varies between 400 and 1600 kg/m^3. It can be used for structural, partitioning, insulation and filling applications with excellent acoustic/thermal insulation, high fire resistance, lower raw material costs, easier pumping and finally no compaction, vibration or leveling [1,3].

It emerges as an economical and innovative contribution to the production of lightweight building blocks, partition wall systems, panels, walls, blocks, road fill and roof insulation. It is effectively deployed in countries such as Turkey, Germany, England, Thailand and the

Philippines. It is preferred for the production of foam concretes, bridge fill, insulated wall panels and floor insulation [5]. Researchers show interest in high energy-saving materials in terms of energy savings. In this respect, foam concrete, which is a lightweight, porous material with a high strength-to-weight ratio, stands out. It is widely used in modern buildings. It also offers advantages, such as transportation, cost and production [6].

The Romans made a concrete mixture (made of lime, water, small gravel and coarse sand) into which they mixed animal blood. They discovered that the added animal blood produced air bubbles, making the mixture more useful and durable. It is thought that a similar technology was used by the Egyptians 5000 years ago [7]. The first skate on foam concrete was bought by Axel Ericson in 1923. Wall panels and floor boards were used in commercial and residential buildings by the Soviet Union in the 1930s. In 1950, aerated concretes produced for carrier elements prepared using coal slag were put on the market. For foam concrete, the first scientific research was conducted by Valore in 1954. Hydrolyzed protein agents that improve the stability of air cells were introduced to the market at the end of the 1950s. By the end of the 1970s it was used in oil well cementing projects and excavation projects [1,7,8]. Some properties of foam concrete are given in Table 1.

Table 1. Some properties of foam concretes reviewed.

References	Year	Content	FUW	MC	FC	RT	DS	WP	PRS	HUW	AVC	MST	THP	SEM	FR	FT	ACP
[9]	2018	OPC, BT	✓			✓			✓	✓	✓	✓	✓				
[10]	2011	OPC, SND	✓						✓	✓			✓		✓		
[11]	2018	PC, FA, SND	✓							✓		✓					
[12]	2019	OPC, RGP	✓				✓	✓		✓		✓					
[13]	2013	OPC, SND, FA								✓		✓			✓		
[14]	2017	OPC			✓	✓					✓	✓					
[15]	2016	OPC, SA	✓					✓	✓			✓		✓			
[16]	2021	OPC, SND	✓					✓	✓	✓		✓	✓	✓	✓	✓	✓
[17]	2015	FA, BFS					✓	✓	✓			✓	✓	✓	✓	✓	
[18]	2021	OPC, RHA, WMP, SND						✓	✓			✓	✓				
[19]	2021	RHA, GGBFS, FA	✓			✓								✓			
[2]	2021	OPC					✓					✓		✓			
[20]	2021	PC, FA			✓							✓					
[21]	2021	OPC, FA	✓				✓	✓	✓			✓	✓		✓		
[5]	2021	WPC, GGBFS, WMP, BF					✓	✓	✓			✓					
[22]	2020	PC, FA, CBP, CDW										-		✓		✓	
[23]	2019	PC, SND, SF, SP						✓				✓	✓	✓	✓		
[24]	2021	MT, RS, EPS			✓							✓					
[25]	2019	OPC, SND, RP	✓		✓				✓	✓	✓	✓	✓	✓			
[26]	2019	OPC, FA	✓					✓		✓		✓					
[27]	2007	OPC, SND, FA		✓	✓	✓		✓				✓					
[28]	2005	OPC, SND, FA	✓		✓	✓		✓				✓					
[29]	2005	OPC, SND, FA	✓					✓		✓		✓				✓	
[30]	2004	OPC, SND, FA									✓			✓			
[31]	2015	OPC, SND								✓		✓	✓	✓			
[32]	2016	OPC, FA, BFS, QL						✓				✓		✓			
[33]	2019	OPC, SND	✓		✓			✓		✓	✓	✓	✓				
[34]	2014	FA, BFS	✓		✓				✓		✓	✓					
[35]	2019	OPC, SND	✓		✓		✓	✓			✓	✓		✓		✓	
[36]	2018	OPC	✓			✓			✓	✓	✓	✓	✓				

Today, understanding the properties of foam concrete is of interest to researchers, and many studies focusing on different properties of foam concrete are being conducted. The properties of foam concrete vary depending on many factors. Factors such as foam type, cement type, mineral additives, aggregate type, and the properties of the air spaces created directly affect the strength, fresh and hardened properties of foam concrete. This review article examines the materials that make up foam concrete, their fresh and hardened properties, the changes in their strength and microstructure.

2. Compositions of Foam Concrete

2.1. Cements

In addition to OPC, magnesium phosphate cement (MPC), sulfoaluminate cement (SAC), and fast-setting Portland cement are used in foam concrete production. Different cement types of foam concrete have an effect on setting time, strength, thermal conductivity [37–39]. For example, Li et al. [12] concluded that for a certain dry density or a certain thermal conductivity, MPC foam concrete has a higher compressive strength compared to OPC foam concrete [40]. The strength of OPC develops slowly, while for SAC-based foam concrete, the strength develops early, but in the future, the phenomenon of retraction will occur in the strength development. MPC, on the other hand, has the characteristics of rapid development of strength and no retraction in strength [40].

In the study conducted by Ma and Chen [41], the thermal conductivity of foam concrete prepared using 10% fly ash and MPC increased the compressive strength and thermal conductivity by 25% and 9.1%, respectively, compared to those without fly ash. The reason for this can be shown as the participation of fly ash in the hydration mechanism and improving the pore structure. However, with the increase in the amount of fly ash, a decrease in the compressive strength occurred. This situation may be due to the decrease in the amount of cement. In the study, the effect of silica fume was also investigated, and it was reported that silica fume reduced the compressive strength and thermal conductivity. As reported in the literature, silica fume may decrease the mechanical properties of the MPC mortar because amorphous silica of SF (silicon dioxide) does not contribute to the hydration products of MPC [41]. In this manner, the reason also can be that the decrease in the MAP ($MgNH_4PO_4·6H_2O$) (hydration product of MPC) amount causes a decrease in the compressive strength [41].

It is also reported that geocement and alkaline Portland cement can be used to increase the fire resistance of foamed concrete [7]. The use of supplementary binder components contributes to the reduction in cement consumption [42]. In addition, mineral additives are used to increase the consistency, adjust the hydration temperature and change the compressive strength values. The strength development of foam concretes prepared using fly ash is slow [21,43]. The spherical shape of the fly ash increases the fluidity [11,21]. They also reported that the use of coarse fly ash in foam concrete has a positive effect on increasing workability, mechanical properties and freeze–thaw resistance, and has a negative effect on drying shrinkage and water absorption. However, in different studies, it was reported that the strength increase at early ages is slow and that the strength increases in the long term [21,43]. Temperature development during hydration is reduced by the use of fly ash [44]. In order to reduce the hydration heat of foam concrete, SF, GGBFS and FA up to 10% to 75% of the cement weight is used instead of cement [45].

Zhihua et al. used granulated blast furnace slag for adjusting the rate and the amount of hydration heat of foam concrete. It was also used for controlling the temperature rise to prevent the newly placed foam concrete from deforming and cracking in an uneven volume [46]. The use of silica fume was reported to improve strength by 20–30% [47]. At the same time, in the study of Gökçe et al. [48], the use of silica fume increased the density, compressive strength and thermal conductivity in constant foam content. Bing et al. [49] reported that silica fume increased the compressive strength and splitting tensile strength. SAs improve the hydration reaction and lead to fine hydration products that affect the air void structure and reduce the rheological properties [15].

The superplasticizer is used for reducing the water to cement ratio (w/c) of the cement mix slurry as much as possible while maintaining satisfactory fluidity to allow the foam to be easily produced and disposed of homogeneously between the newly placed foamed concrete matrix [46].

2.2. Aggregates

Coarse aggregates are not deployed in the production of foam concrete. Generally, fine aggregates with a maximum particle size of 5 mm are used. The main reason for this can be that coarse aggregates settle in the lightweight mix and cause the foam to settle during mixing. In addition, fine aggregates should not contain harmful reactive substances that will cause the concrete to expand [4,50]. The replacements of aggregates, in terms of sustainability, partially or completely with recycled materials (such as glass waste, lime, broken concrete, ceramic pieces, and waste marble dust) have positive effects on foam concrete properties [4]. The workability of foam concrete decreased with the use of WMP as fine aggregate [5]. The use of RCA as a fine aggregate due to its empty texture increased porosity [51]. The stability increased with the replacement of sand with RCA as fine aggregate. It contributed to the formation of a more stable system by improving yield strength. However, with the increase in the amount of RCA, a decrease in strength occurred [19]. The optimal utilization ratio suggested of waste clay brick as a coarse aggregate is 25%. However, as the ratio is increased, the water absorption is increased and the compressive strength is decreased [52]. The use of various aggregate types in foam concrete is given in the Table 2.

Table 2. Various types of aggregate.

References	Aggregate Type	Effects on Foam Concrete
[53]	Biomass aggregate	It increased strength both indoors and outdoors.
[29]	FA	Increased consistency and rheology were demonstrated with the addition of FA. There is a need for more foam for the desired plastic density. Especially after 28 days, its compressive strength was higher than sand concrete.
[54]	RHA	It increased its compressive strength. This situation is attributed to the pozzolanic property of rice husk ash.
[55]	EVP	The unit weight of the foam concrete was affected due to the water holding capacity of the EVP. It caused micro-cracks at high temperatures. It was reported that EVP is promising in terms of thermal conductivity and its soft structure may adversely affect the compressive strength.
[12]	RGP	Glass dust caused a decrease in the density of the foam concrete. It is recommended to use 20% glass powder in terms of compressive strength. The reason for this was shown to be that more glass powder causes a decrease in compressive strength and increases the hydration temperature. In addition, glass powders with a particle size of less than 45 µm have a pozzolanic effect. Glass powder, which has a pozzolanic effect, has an improving effect on compressive strength.
[25]	RP	Increasing the amount of rubber powder decreased the workability. It increases the compressive strength and tensile strength, but the increase in its amount causes the compressive strength and tensile strength to decrease.
[18]	WMP	It reduced the collapse value. It contributed to the reduction of drying shrinkage and increased freeze–thaw resistance. It improved mechanical properties.
[56]	Quarry wastes	Quarry dust reduced flowability and it increased compressive strength and thermal conductivity.
[51]	RCA	The porous structure of recycling concrete wastes increased the porosity of the foam concrete. Therefore, water absorption increases, and ultrasound speed and thermal conductivity decrease. However, foam concrete containing up to 50% recycling concrete wastes exhibited a compressive strength similar to control foam concrete.

2.3. Foam Agents

One of the most important components of foam concrete is foam, and foaming agents are used to produce the foam [3]. Foaming agents affect the density, porosity, stability, and fluidity of foam concrete. Their main task is to introduce air bubbles into foam concrete. Foam can be produced in two different ways, as pre-foaming and mixed foaming methods.

Foaming agents can be synthetic, glue resins, protein based, detergents, resin soap, saponin, and hydrolyzed protein. However, the most commonly used foaming agents are synthetic and protein-based ones [2,3,57]. Protein-based agents allow a stronger pore structure and more closed void space network. It creates a more stable air-void network. Synthetic agents, on the other hand, allow more expansion, so they have lower densities. Synthetic agents are more economical and easier to use than protein agents and also require less energy for storage [3,4,7,57]. Falliano et al. [38] reported that a constant water/cement ratio resulted in more stable foam concrete samples than those obtained from protein ones.

Ranjani and Ramamurthy [58] carried out the analysis of the foam produced using sodium lauryl sulfate (SLS) as surfactant. As a result, the foam produced with SLS could not keep the liquid in the foam, thus leading to a 40% reduction in density after 0 min. It also was reported that as the dilution amount of SLS increases, the drainage increases. In the study conducted by Ma and Chen [41], sodium bicarbonate (NAC) was used as a foaming agent. It was reported that dry density, compressive strength, burst tensile strength, thermal insulation, and water resistance decrease due to the increase in the amount of NAC. Four types of foam were used in the study. Sodium dodecyl sulfate (SDS) as anionic surfactant, cetyltrimethyl ammonium bromide (CTAB) as cationic surfactant, emulsifier OP-10 nonionic surfactant and hydrolyzed protein (HP) were selected as amphoteric surfactants. The study reported that cement hydration would be clearly delayed by HP or SDS and that CTAB or OP-10 had little effect on cement hydration [2].

The interaction between the foaming agent and cement is an important point for foam concrete. Gas–liquid interface properties affect the performance of foam concrete. In foam concretes prepared with cationic or non-ionic surfactants, interconnected pores usually occur and have a low bulk feature. When low density foam concrete is desired to be produced, cationic or non-ionic foaming agents can be used [2]. The different foaming agents affect foam stability. The presence of stabilizers, such as nanoparticles, has a positive effect in preventing the collapse of the foam and strengthening its stability [36]. Sun et al. [36] concluded that the stability of synthetic foams is higher when compared to synthetic and natural-based foams. This proved to result in a smaller pore size and high compressive strength. The interaction between the foaming agent and cement has a large share in the formation process of foam concrete [2].

2.4. Fibers

Fibers are used to improve the mechanical and strength properties of concrete. They are divided into natural and artificial types. Examples include alkali-resistant glass, coir fiber, steel, carbon, palm oil and polypropylene fiber [57]. The use of fibers helps to improve compressive strength and limit crack formation. However, it causes less workability and difficulties for compaction [59].

In the study in which the hybrid use of polyvinyl alcohol fiber (PVA) and coir fiber was carried out, it was suggested that the use alone for both fiber types should be 0.3%. With the use of PVA fiber, 76% more strength was obtained compared to the control sample and it performed better than coir fiber. The reason for this is that PVA fiber has higher tensile strength [60]. It was reported that polypropylene fiber increases the compressive and splitting tensile strengths [49]. The mechanical properties of sugar cane pulp fiber reinforced foam concretes were improved. However, it increased the water absorption rate [61]. With the use of carbon fiber, the modulus of elasticity increases, and flexural strength improves [62]. Some examples used in other studies are given in Table 3.

Table 3. Some examples of fiber reinforced foam concrete studies.

References	Fiber Type	Effect
[63]	Steel	The use of steel fiber has significantly increased ductility and rupture modulus. However, it did not have a significant effect on compressive strength.
	Polypropylene	Polypropylene fiber increased tensile strength and modulus of rupture. There was no significant effect on compressive strength and flexibility modulus.
[49]	Polypropylene	It improved the strength of foamed concrete. It reduced workability. It improved drying shrinkage.
[64]	PVA	It significantly improved mechanical behavior.
[65]	Nylon	It increased the ductility index.
[66]	Natural (Miscanthus)	It increased its compressive strength. It was reported that a sustainable geopolymer concrete can be developed with thermal insulation.
[67]	Polypropylene	The geopolymer foam reduced the drying shrinkage of the concrete and increased the compressive and bending strength.
[68]	Rice straw	It contributed to the development of acoustic and thermal properties.
[69]	Cellulose	It increased compressive strength by 35%, increased the stability of the foamed concrete mix and reduced shrinkage deformation.
[70]	Hemp	It provided very large compressive and flexural strength enhancements.
[5]	Basalt	The flexural and compressive strengths increased.
[71]	Glass	Improved the bending capacity of the beams.

3. Properties of Fresh Foam Concrete

3.1. Workability

With the increase in density, the spread of light concrete increases. Foam concretes with low densities have high foam content. Therefore, the mixtures become harder, causing a decrease in the settling flow [5,21]. The use of fiber reduces the workability of foam concrete, and it may be necessary to increase the amount of superplasticizer to provide workability [47]. The increase in the w/c ratio causes the water film on the particles to thicken. Thus, the viscosity decreases, and the diffusion of foam concrete increases [72].

In the study where ceramics thinner than 4.75 mm were used, the ceramics were partially replaced by river sand. The ceramics used have high water absorption capacity. For this reason, it was observed that some of the water used to maintain the fluidity of the mixture tends to be retained by the ceramics. This situation caused the slump values to decrease [73]. Similarly, in Bayraktar et al. [5]'s study, waste marble powder was used as a fine aggregate partially replacing sand and it was observed that WMP reduced the slump values. It was reported that the reason for this is the angular grain structure of WMP aggregates. Due to its angular shape, more surface area has to be lubricated, which reduces workability [5]. The small diameter of the aggregate used increases the aggregate surface area. Increased surface area causes more water demand and reduces workability. Inert dust has a smaller particle diameter than sand and using inert dust instead of sand reduces workability. Superplasticizers should be used in order to achieve the desired workability. For this reason, it is difficult to obtain foam concrete with a high dust content [35]. The use of superplasticizer provides the desired workability with the presence of low water content [16]. Workability characteristics reported for different flow values are given in the Table 4.

Table 4. Workability of foam concrete based on flow [74].

Flow Values (%)	Description
0–20	Very Low
20–40	Low
40–60	Medium
60–80	High
80–120	Very High

3.2. Consistency

The fresh state properties of foam concrete are evaluated in terms of two factors; consistency and stability. Using Marsh cone and flow cone diffusion tests, the flow times of foam concrete are obtained, so the consistency of the foam concrete can be evaluated [1]. When the flow time value of foam concrete is below 20 s and the flow value is between 40% and 60%, it was found that it is good in terms of consistency [74]. In the study using modified marsh cone (Figure 1), the behavior of the foam concrete according to the flow time is classified as given in Table 5.

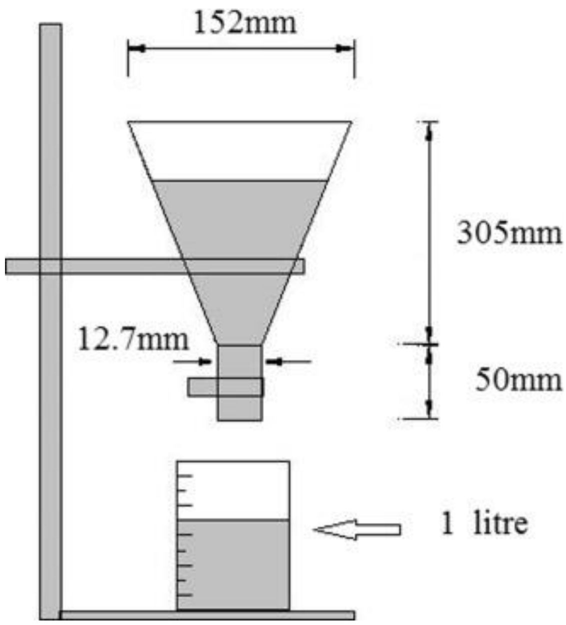


Figure 1. Modified Marsh cone [11].

Table 5. Classifications of foam concrete with respect to the flow time [11].

Main Class	Description	Description
1	1 L $\leq$ 1 min	Constant flow
2	1 L $\geq$ 1 min	Interrupted flow
3	0.5 L $\leq$ Efflux $\leq$ 1 L	Completion of flow after tamping gently
4	Efflux $\leq$ 0.5 L	Limited flow
5	Efflux = 0 L	No flow

As a filler, the coarse FA spread 2.5 times more than the cement–sand mixture. It has been stated that this is due to the particle shape and particle differences of fine aggregates [1]. Similarly, Wei She et al. [11] in their study where FA was used as a fine aggregate, the use of fly ash increased the fluidity. The reason for this can be shown as FA having a spherical shape [11,21,29]. The use of fine FA instead of sand results in a decrease in the consistency of the mixture due to the high fineness. In other words, the water–solid ratio should be increased in order to meet the consistency requirements. The increase in the water/binder ratio increases the fluidity of foam concrete. However, it can also cause the particles to bleed and segregate [21]. In the work carried out by Nambiar and Ramamurthy [75], the consistency of the base mixture was significantly reduced with the addition of foam. It was reported that this is due to the reduced self-weight and the greater cohesion provided by the higher air content [1,21,75].

3.3. Stability

It was reported that there is a 45% spread as the appropriate workability value of foam concretes with the use of typical materials [1]. The foam used can have different effects on stability. Hashim et al. [20] established a test system to evaluate the stability of foam produced using protein and synthetic foaming agents. Both foams were placed in beakers with a capacity of 1000 mL, and balls of equal weight and diameter were placed on them. The contact times of the balls to the bottom base of the beaker were recorded. In this way, the sinking time of the ball and the stability of the foam could be evaluated. At the end of the test, the ball sinking in protein-based foam took 19 min, while it dipped in synthetic foam for 13 min, and it was concluded that the stability of the protein-based foam was better. The reason for the better stability performance of the protein-based foam is that the protein adsorbed at the interface forms a viscoelastic layer with high surface shear viscosities, resulting in stable air bubbles in the Plateau Limits. It made it more stable [20].

The use of nanoparticles can be used to improve the stability of foams. Sun et al. [36] used synthetic surfactant (SS), plant surfactant (PS), and animal surfactant/blood-based surfactant (AS), and the mean disappearance rates of SS, PS and AS foam were respectively 0.25%/min, 0.6%/min and 0.5%/min. SS showed the best foam stability performance. The reason for this is that the SS foam is stabilized with nanoparticles.

The increased foam content increases the water-to-solid ratio requirement of the main mix. The adhesion between the bubbles and the solid particles in the mixture increases the stiffness, which affects the stability of the mixture, causing the bubbles to segregate during mixing [76]. In the study using NAC as a foaming agent, it was reported that if the NAC content is more than 5%, it segregated in the foamed concrete samples. It was reported that the probable reason for this may be the excessive amount of gas that cannot remain constant due to the excessive expansion of the bubbles by heat dissipation [41].

The use of magnetic water significantly increased the stability of foam concretes produced with synthetic foam. However, it had a negative effect on protein-based foams. The reason for the positive effect of the tap water passing through the magnetic field on the stability of the foaming agents is the strengthening of the hydrogen bonding of the water passing through the magnetic field [77].

The type of aggregate used also may affect the foam stability. With the use of recycled concrete aggregate in geopolymer foam concrete instead of fine sand, the depth of defoaming decreased and the stability increased. Additionally, the use of RCA improved the yield strength. In this way, a more stable and uniform air void system is obtained [19].

It was reported that adding 1–2% of the setting accelerator causes segregation, but more stable results are obtained with the use of dosages of 2%. The set accelerator improves the degree of clumping of hydration products and increases the resistance of the foam to changes. In this way, the stability of the foam is increased, and the coalescence and crushing of the preformed foam can be prevented. From a thermodynamic perspective, as the amount of hydration products formed on the surface of the bubbles increases, the gas–liquid interface energy of the air bubbles decreases and the stability of the foam increases [15]. Superplasticizers were reported to allow the w/c ratio to drop below 0.3 and provide 43% increase in stability. The increase in w/c causes difficulties due to overlapping of hydration products and a decrease in torque associated with the slurry. It was reported that the low torque achieved at w/c = 0.1 caused a decrease in stability and segregate [15].

4. Physical Properties of Foam Concretes

4.1. Dry Unit Weight (Density)

The density of foam concrete can be evaluated under two headings as fresh and dry density. It is recommended that the difference between fresh and dry density is 100–120 kg/m^3. Dry density controls the mechanical, physical and durability properties of foam concrete, while the fresh density ensures the volume required for the design mix and pouring control [57].

According to the literature, the dry density of foam concrete is directly affected by the amount of foam. Increasing the amount of foaming agent produces more foam, resulting in a larger sample volume. In this case, the dry density of the samples decreases. Compressive strength has a linear relationship with dry density [21,41,46,59]. Compressive strength increases with increasing dry density. In addition, the increase in dry density provides an increase in thermal conductivity [17].

Density may be affected by gradation and fine aggregate type. It was reported that the density increased as the aggregate ratio increased [57]. Other components used in the preparation of foam concrete also affect density. Adding silica fume to foam concretes prepared with fixed foam content increases the density [48]. Similarly, it was reported that when more than 30% slag was used instead of FA in geopolymer foam concrete prepared with FA, the density decreased [17]. It was reported that there is a relationship between fresh and hardened density of foam concretes with different ash contents. As a result, an equation was proposed to calculate the required pouring density for the dry weight of concrete between 600 and 1200 kg/m^3 [7]. Some unit weight values obtained from different studies are presented in Table 6. Cast density is calculated as (ρ_{cast} = cast density; ρ_{dry} = dry density) in Equation (1).

$$\rho_{cast} = 1.034\rho_{dry} + 101.96 \quad (1)$$

Table 6. Unit weight of foam concretes in the literature.

References	Unit Weight (kg/m^3)
[78]	868.8–2225
[51]	594–605
[5]	1679–2033
[55]	587–1040
[10]	650–1000
[1]	240–1350
[79]	800–1320
[80]	650–1000
[9]	300–850
[81]	100–300
[57]	280–1840
[45]	400–1200
[11]	970–1350

4.2. Drying Shrinkage

Foamed concretes have the disadvantage of high drying shrinkage and are affected by foam volume, aggregate type, mineral additive, fiber content and water content. The cracking phenomenon is particularly related to the uneven volume change during the curing process due to the temperature difference caused by the heat of hydration under the thermally semi-adiabatic condition of the matrix [46].

The shrinkage in foam concrete is a function of the foam volume. Therefore, it is related to the paste amount and paste properties. Nambiar et al. [75] reported that although removing water from relatively larger artificial air pores does not improve shrinkage, artificial air voids may indirectly have some degree of effect on volume stability by enabling some shrinkage occurrence. This situation occurred more frequently at a higher foam volume [75].

Drying shrinkage increases with increasing density of foam concrete [59]. Higher amount of foam with lower densities reduces the amount of cement. Thus, the hydration products are reduced, and less shrinkage occurs [20]. The reason why the foam used has an effect on drying shrinkage may be the pore structure that occurs. It was reported that the pore size and pore attachment increased with increasing the amount of foam, thus decreasing the shrinkage [75]. A lower pore connection may help reduce drying shrinkage [36].

An amount of shrinkage varying between 0.1% and 0.35% of the total amount of hardened foam concrete occurs. The main method used to prevent shrinkage is the use of fiber. The fiber-containing foam concrete resists shrinkage, resulting in less drying shrinkage. The increase in fiber content helps to increase the resistance to drying shrinkage and reduces the amount of shrinkage that occurs [61]. The type of fiber used may show different performance regarding shrinkage. Raj et al. [60] reported the effects of PVA fiber and coir fiber on the drying shrinkage of foam concrete. The use of PVA fiber increases drying shrinkage. The reason for this was shown to be that early on, the PVA fiber retains water and shrinks, releasing the water as the concrete hardens. Reduced drying shrinkage was experienced with the use of coconut fiber. The fact that coconut fiber has water-retaining properties explains this situation. The use of sugar cane fiber also limits the changes in foam size, reducing soot shrinkage [61].

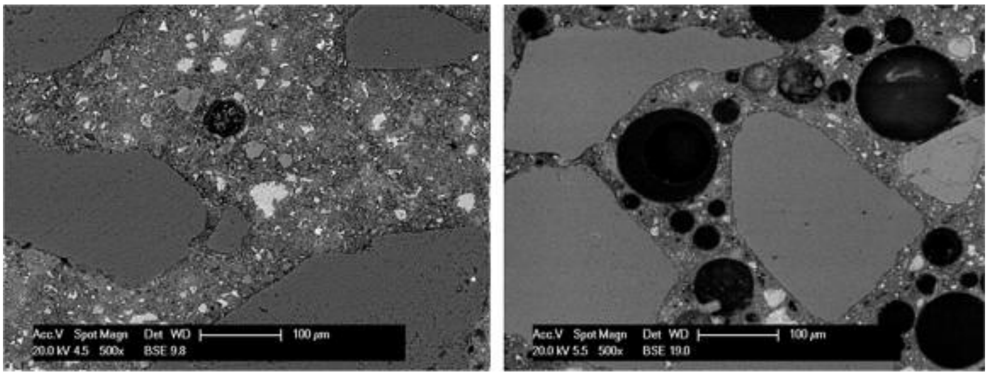
FA has negative effects on drying shrinkage. In the study where FA was used as fine aggregate, there was an increase in drying shrinkage with the use of FA. This is due to the greater presence of free water in FA pastes and therefore more evaporating water [11,75,82]. The use of clay brick powder from construction and demolition waste as additional cement material was reported to improve the drying shrinkage behavior of foamed concrete [22]. Drying shrinkage of foamed concrete was reduced when silica sand was replaced with WMP. The reason for this may be the grain shape of the WMP and the pore size distribution of the foam concrete. As mentioned earlier, the pore structure affects drying shrinkage. The improvement in the pore structure reduces the drying shrinkage thanks to the decreased evaporation from the capillary pores [5].

4.3. Air Void Structure and Porosity

The strength and durability properties of cement-based materials are affected by the porosity, permeability, pore size and distribution of the material [27]. If we consider the pore structure of foam concrete in general, it has three types of porosity: gel pores, capillary pores and air pores [83]. While capillary and air pores affect the strength properties of foam concrete, gel pores have no effect on the strength [27]. The pore distribution and size of the foam concrete directly affect its mechanical and physical properties. Therefore, the properties of the porous structure are very important for foamed concrete [20]. The SEM images in Figure 2 can be shown as an example of the pore structure formed by the addition of foam [84].

When compared to synthetic-based foaming agents, protein-based foaming agents create smaller and homogeneous air spaces at high foam concrete densities [8]. In the study conducted using synthetic, plant and animal glue/blood-based surfactant, the pore walls of foam concrete containing SS were thicker and less connected than others. The smaller pore size of the SS-containing foam concrete and its low pore connection enabled the foam concrete to gain features such as high compressive strength, low water absorption and stronger frost resistance [36].

The air voids in the hardened concrete have two different effects on the concrete. On the one hand, the strength decreases with the increase in air content in concrete. Additionally, in hardened concrete, a well-designed air system can improve freezing–thawing resistance [40]. Providing an optimal air void system in foamed concrete is very important to produce a material with a high strength/weight ratio [48].



(a) (b)

Figure 2. (**a**) Reference mixture containing no foaming agents or foams SEM images, (**b**) foamed concrete mixture SEM image. Reprinted/adapted with permission from Ref. [84]. 2015, Elsevier Science & Technology Journals.

The narrowness of the air voids contributes to the increase in strength. With the increase in the amount of foam, mixtures with narrower air void size distribution show higher strength [27,84]. Increasing the foam dosage increases porosity [59]. Hashim and Tantray's [20] study compared the performance of protein and synthetic foaming agents. As a result of the study, it was reported that the size of the air voids increased with the decrease in the density of the foam concrete for both types of foam. The reason for this can be shown as the amount of foam increases, there is an increase in the amount of air voids, and therefore the overlapping of the air voids can be combined. The combined air spaces create a wide distribution of pores, which results in lower strength [27].

In the use of glass and plastic wastes as filling material, glass wastes provide more uniform distribution of voids and a less interconnected void structure. This is attributed to the finer glass waste powder. It was reported that thinner fill materials create uniform air pockets [85]. The use of fly ash as a filler provides a more homogeneous distribution of air voids compared to fine sand. It provides a good and homogeneous coating on the bubble, preventing bubbles from overlapping and coalescing, thus helping to distribute the air voids evenly [27]. Nambiar and Ramamurthy reported that FA [27], when used in foam concrete, provides a good homogeneous coating on each bubble, and that these coatings help the uniform distribution of air voids and prevent blisters from coalescing. These properties lead to higher strengths.

The increase in the amount of water provides the enlargement of the air voids [15,80,86,87]. Growing pores have less void surface area. In addition, the increase in the amount of water increases the number of capillary pores. In fact, for the same porosity, the increased fraction of capillary pores leads to a decreased number of air pockets. The pore size is reduced by the use of SA. Increased amounts of SA also result in increased ability of the slurry to contain air bubbles and as a consequence, the size of the pores is decreased [15]. The use of superplasticizer helps in improving the void structure [84]. With the increase in superplasticizer content, it provides lower water consumption, thus, a better pore structure, thicker porous wall and a stronger matrix are formed. In this way, foam concrete demonstrates higher strength [16].

Porosity is accepted as a main parameter that directly affects the physico-mechanical, thermal and durability properties of foam concrete [51]. The type of aggregate used affects the porosity. The pore structure of the aggregate type used affects the porosity of the foam concrete [51,86]. The use of RCA as fine aggregate was investigated in the study of Gencel et al. [51] As a result of the study, an increase in apparent porosity occurred with the use of RCA. This situation was attributed to more porous texture forms than natural sand.

By using the RCA as a fine aggregate in geopolymer foam concrete, a more homogeneous pore distribution was achieved. In addition, thinner air pockets occurred in RCA-containing foam concretes. This can be attributed to the greater stability of the samples containing RCA. In stable mixtures, thinner and homogeneous distribution of air voids occurs [19]. In the use of glass and plastic wastes as filling material, glass wastes provide more uniform distribution of voids and a less interconnected void structure. This was attributed to the finer glass waste powder. It was reported that thinner filling materials create uniform air pockets [85]. The use of waste marble dust and RHA in foam concrete reduces porosity. Materials with pozzolanic properties improve the interfacial transition zone, thanks to the filling effect. Thus, it was reported that it provides a filling effect that reduces porosity by providing effective particle packaging [18]. The porosity percentages of different studies are given in Table 7.

Table 7. The porosity percentages of different studies.

References	Porosity (%)
[86]	48.9–52.8
[87]	84.78–93.30
[55]	70.6–89.5
[9]	35–85
[80]	50–80
[10]	50–75
[16]	17–24
[5]	31.1–24.4
[81]	70–81
[88]	90.7–91.6
[87]	84.78–93.30

4.4. Water Absorption

Foam concretes designed for interiors, such as wall elements inside the building, are generally not exposed to water. In such cases, water absorption is not important, as foam concrete will not be affected by freezing–thawing. In this context, the water absorption is important as freeze–thaw effects posing a threat to foam concrete if it is used as an external element. Foam concretes used as external elements and structural elements are required to have low water absorption values [55]. The water absorption property of concrete is directly related to the spaces and pores in it. The connection of the pores with each other can have an effect of increasing water absorption. However, the presence of capillary voids within the concrete directly increases water absorption [74,89]. Air voids from the foam do not contribute to water absorption [74]. Increasing the paste amount increases the number of capillary pores in the foam concrete content. This allows greater capillary forces to occur [11]. The penetration of water into concrete is not only dependent on the connection of porosity and pores; the pore diameter and distribution of pores also affect water absorption. With the increase in the w/c ratio, the absorption increases [55].

Ma and Bing [90] reported that water absorption increased significantly with increased foam volume in soil-based foam concrete. This is because the more stable foam increases, the more interconnected pores are formed. They also reported that the use of silica fume reduced water absorption. The time required for water to penetrate the concrete is different from concrete without silica fume. In other words, soil-based foam concrete with silica fume may have more fine and unconnected pores.

The water absorption of the foam concrete increased by using the RCA as fine aggregate. The reason for this is due to the high water absorption feature of RCA. In other words, the water absorption properties of the aggregates used affect the water absorption of the foam concrete [19].

In the study performed by Gopalakrishnan et al., FA and quarry dust were used. The quarry dust was used as a fine aggregate partially replaced by sand, and FA replaced cement. As a result of the study, it was seen that the best water absorption performance was achieved in the presence of 30% FA with quarry dust. It was reported that the water absorption was directly related to the density of the foam concrete [91].

Fibers added to foam concrete can increase water absorption. In connection with the water absorption properties of the fibers, there is an increase in water absorption. As it is known, natural fibers have water absorption properties. For example, in foam concrete where sugar cane pulp fibers are used, the rate of water absorption is increased for this reason [61].

5. Mechanical Properties of Foam Concrete

5.1. Compressive Strength

Compressive strength is affected by parameters such as density, mixture components used, aggregate, mineral additive, water content, foam, curing and porosity. The amount of water has a significant effect on the compressive strength of foamed concrete. It was reported that small changes in the water content of foam concrete do not affect the strength as in normal concrete [1]. An increase in the w/c ratio can provide an increase in strength. The reason for this can be demonstrated by the formation of pores that grow with the amount of water. With the increase in large pores and capillary pores, the density of the air voids decreases and the strength increases [15]. Liu et al. reported that the compressive strength of foam concrete showed an inverted V-shaped change with the increase in the water/cement ratio. If the w/c ratio is below the optimal limit, thinner-walled and irregular foams occur, and the compressive strength is negatively affected. The use of the w/c ratio above the optimal limit results in a poorer bubble holding ability. It causes pores to join and uneven distribution. This irregularity in the pore structure is subjected to stress concentrations. In addition, the increase in the amount of water triggers the formation of capillary channels, thereby reducing its strength [72]. The use of superplasticizer contributes to the increase in compressive strength by reducing the w/c ratio [85].

The aggregate type used is effective on the strength. Gencel et al. [51] used RCA that increased the porosity, and this situation caused a decrease in the compressive strength. Similarly, Pasupathy et al. [19] used RCA in geopolymer foam concrete. RCA content reduced compressive strength. This is because the strength of RCA particles is lower than sand. In addition, adding more water to obtain workability in RCA samples also negatively affected the strength.

Thanks to the pozzolanic properties of FA, its use in foam concrete as fine aggregate contributes to the compressive strength [11]. Ramamurthy and Nambiar's [79] study investigated the effect of the additive type on the compressive strength of foam concrete. The compressive strength of the samples using FA as filler material showed higher compressive strength values than those prepared with sand. Due to the late pozzolanic reaction of FA, the increase in compressive strength continues with the advancing age. When FA was used as filler, it was reported that the compressive strength of foam concrete was 1.7 and 2.5 times higher on the 56th and 180th days compared to the 28th day [29].

The use of mineral additives affects the compressive strength. The use of silica fume in foam concrete increases the compressive strength [48]. Compressive strength in soil-based foam concrete increased with the use of silica fume and quicklime. It was reported that it increased from 4 MPa to 7.8 MPa with the addition of 20% silica fume. This may be thanks to the finer pores caused by silica fume [90].

In the study of Bing et al. [49], the 7-day compressive strength of samples containing FA showed 85–90% of the 28-day compressive strength. In samples without FA, this rate decreased to 75–80%. The compressive strength of the geopolymer foam concrete prepared with the addition of FA reached 7.5 MPa in 28 days. With the addition of 20% slag to FA, the compressive strength increased to 12.6 MPa. However, adding more slag slightly reduced the compressive strength [17].

Additives added to foam concrete affect strength. It is obvious that the superplasticizer causes higher strengths thanks to the lower void size and pore connectivity [38]. Using SA reduces pore size. For this reason, the increase in dosage causes the strength to decrease [15].

Comparing foamed and non-foamed samples, as expected, the compressive strength of foamed samples is lower. The amount of slurry decreases as the amount of foam used increases. This situation causes a decrease in dry density. There is a linear relationship between the dry density of the prepared foam concrete and its compressive strength. As the dry density increases, the compressive strength increases [15,21,38]. In addition, the porosity increases with the increase in the amount of foam. Increasing porosity causes an increase in the amount of air voids, thus decreasing the compressive strength. On the contrary, when the amount of foam is reduced, the amount of cement used increases, thus increasing the compressive strength [5,15,21].

The type of foam used also affects the strength. Looking at the studies in the literature, protein-based foaming agents provide better compressive strength than synthetic ones. Falliano et al. [38] reported that foam concrete containing a protein-based foaming agent, with a w/c of 0.5, showed higher compressive strengths, and a synthetic-based foaming agent, with a w/c of 0.3, led to higher compressive strengths. He observed that protein-based foaming agents increased the compressive strength of foam concrete.

The curing method applied to the samples affects the strength. Air, water and cellophane curing methods were used in the studies. It was observed that the air curing method resulted in the lowest strength values. The reason for this is the lack of optimal conditions for the hydration of the samples [15,38]. In contrast, the strength of standard curing and moisture-proof cured samples increased with increasing curing age [15].

The addition of fibers can help limit crack propagation, thereby helping to increase compressive strength. The use of basalt and PVA fibers increases the compressive strength [59,60]. A 38% increase in compressive strength was achieved by using 1% of sugar cane pulp fiber. Compressive strength is adversely affected by increasing the amount of fiber. As workability decreases, the need for water increases, which negatively affects the strength [61]. Compressive strength values for different studies are given in Table 8.

Table 8. Compressive strength values for different studies.

References	Cement and Additives	Aggregate	Superplasticizer	Foaming Material Type	w/c	Density (kg/m^3)	Compressive Strength (MPa)
[46]	PC − GGBFS	-	✓	H_2O_2	-	150–300 (dry)	0.41–0.79
[35]	PC	Inert powder − Sand	✓	Protein	0.5–0.4	1600–1300 (fresh)	5.5–24.3
[29]	PC	FA − Sand		–	0.5	1000–1400 (fresh)	3.9–7.3
[85]	PC	Glass	✓	Protein	0.55–0.45	1212–1579	5.28–10.26
		Plastic	✓	Protein	0.75–0.65	803–1250	1.53–6.06
[72]	PC	-		Protein	0.4–0.60	-	0.1–6
[40]	MPC	-		H_2O_2	0.6	300–1000 (dry)	1.8–21.6
[86]	PC − FA	Sand + GBS		Protein	0.55–0.91	975–1132 (bulk)	1.10–1.62
[48]	PC + FA + SF		✓	Synthetic	0.3	873–1998 (dry)	1.5–88.1
[25]	PC	Sand + Rubber	✓		0.45	1800	5.70–17.15 (ave)
[26]	PC + FA		✓	Protein	0.33–0.36	970–1307 (dry)	10.4
[92]	PC	Sand + Rubber	✓	Synthetic	0.38–0.5	1500–1660	6.4–18.3
[93]	PC + GBS + GGBFS	River Sand		Protein	-	1425–1480	2.82–12.48

5.2. Flexural Strength

The ratio between flexural strength and compressive strength of foam concrete is in the range of 0.25–0.35 [1]. When the sand-containing mixtures of foam concrete and the mixtures with FA are compared, higher values are observed in those containing sand. This is thanks to the improved shear capacity found between the sand particle and the paste phase [1]. Flexural strength increases with the increase in dry density. However, adding FA decreases the flexural strength. This is because FA contributes to strength in later ages [21].

The use of fibers improves the flexural strength. It provides the transfer of tensile stresses with the bridging effect, thus increasing the strength. It must be of sufficient length, number, and size in order for the fibers to develop their tensile strength. With the fiber additive, the concrete becomes stronger and more ductile. The fiber improves flexural strength, toughness and improves post-cracking behavior [57]. Mastali et al. [59] increased the flexural strength by a minimum of 25% and a maximum of 400% by using PVA and polypropylene fiber. The use of basalt fibers has a positive effect on flexural strength. This is thanks to the high tensile strength of basalt fibers. The ability of basalt fiber is to resist the crushing of mortar samples, and this was observed to be positive for flexural strength [5]. The use of PVA fiber improved the flexural strength. Increasing fiber content decreased the strength but was reported to outperform the control sample [60]. It was stated that the use of 2% short polymer fiber used in conjunction with the glass type bi-directional grid reinforcement increased the bending strength. It was reported that after a certain amount of fiber (5%), the interaction and strength between the two reinforcement levels would also decrease significantly. Basalt grid and carbon grid foam concrete have an effect on increasing the average collapse load [45]. Water content is another important factor on the flexural and tensile strength of foam concrete. It was reported that excessive amounts of water decrease the flexural strength due to the decrease in the density of the mixture [57].

5.3. Elasticity Modulus

The elasticity modulus of foam concrete varies between 1 and 12 kN/m^2 for a dry density of 500 to 1600 kg/m^3. Generally, the elastic modulus of foam concrete is lower than normal concrete. It was found to be 25% less than that of normal concrete. The reason for this can be attributed to the fact that coarse aggregate is not used in foam concrete production [13,45].

It was reported that the modulus of elasticity increases up to 400 °C and then decreases; similar behavior was observed for compressive strength. The increase in foam ratio decreases the modulus of elasticity [94]. Generally, compressive strength and modulus of elasticity have a linear relationship. Methods that increase the compressive strength in foam concrete generally increase the elasticity modulus. The use of fiber improves the compressive strength as well as the modulus of elasticity. However, depending on the type of fiber used, the increase in elasticity modulus may vary. This may be thanks to the fibers having different stiffness [62]. Similarly, the change in the aggregates used in foam concrete affects the elastic modulus. The use of low elastic modulus aggregate affects the overall material hardness. It was reported that rubber parts replacing sand caused the elastic modulus to reduce [92].

Using FA as a fine aggregate showed a lower elasticity coefficient than sand [45]. In one study, using RCA instead of river sand caused a decrease in the dynamic elastic modulus value. This was attributed to the increased porosity with the use of RCA [51]. In the study carried out by Ma and Chen, the modulus of elasticity gradually increased with the increase in the dry density of foam concrete prepared with MPC. It was reported that higher elastic modulus was obtained compared to foam concrete prepared with OPC with the same dry density [41].

5.4. Models Predicting Strength

According to the Abrams rule, when concrete is fully compacted, strength and w/c ratio are taken in inverse proportion. In 1896, René Féret constructed the following equation with regards to the volumes of water, cement, and air in the mixture [95].

$$f_c = Kcc + a^2 + w$$

where f_c = compressive strength (MPa); c, w, a = absolute volumetric ratios of cement, water and air; and Kcc is used as the Féret constant.

Hoff reported that the strength for any w/c ratio is chemical control, entrained and entrained air content, paste age, cement fineness, curing temperature and moisture. He reported the porosity strength model for Portland cement, preformed foam and produce foam concrete with water [96]. Hengst and Tressler reported that the defect size associated with pore size (at a given bulk density) is an important parameter in controlling the strength of foamed Portland cement [95,97]. It was demonstrated by Kearsley and Wainwright [95] that the compressive strength of foam concrete is a function of porosity and age. The presented multiplicative model (such as the equation derived by Balshin) was reported to be consistent with the results at all ages of up to 1 year. Nambiar and Ramamurthy [98] proposed similar relationships based on Balshin's model and Power's concept of the gel–space ratio. The model, based on Balshin, uses the composition of the components and easily measurable parameters. The proposed model stands out with its good correlation with the measured values and its ease of application. Lian et al. [99] studied the relationship between porosity and strength for porous concrete. A model was proposed for the relationship between porosity and strength. This new model was derived from Griffith's theory, and it was reported that it could provide a better estimate for porous concrete compressive strength depending on material porosity. Nehdi et al. [100] explored the use of artificial neural networks for preformed foam concrete different from traditional prediction methods. For the model developed with artificial neural network (ANN), the cement content, w/c ratio, foam–cement ratio, and sand–cement ratio were used as variables. As a result, it was reported that the compressive strength, foam density, non-foaming density, and production efficiency of foam concrete mixtures were more accurate than the current parametric methods using ANN. Nguyen et al. developed a deep neural network model to estimate the compressive strength of foamed concrete. A high-order neuron was developed to improve the performance of the created model. Compressive strength estimates were made using the data set, and the results obtained were compared with traditional artificial neural networks and second-order artificial neural network methods. The results showed that the model created can predict the strength of foamed concrete with high accuracy. In addition, according to the results, it was reported that the strength of foamed concrete was greatly affected by the density, followed by the water–cement and sand–cement ratios [101]. Kim et al. [102] evaluated the mechanical behavior of foam concrete, a cellular lightweight binder with entrained air spaces, using the phase-domain fracture model in the framework of finite elements. The aim of this study was to investigate the mechanical properties via microstructure analysis derived from X-ray micro-CT to speed up property evaluations in terms of experiments and simulations. In the study, a methodology for determining micro-scale material properties/parameters of foamed concrete is presented to predict the macro-scale mechanical behavior. The study confirmed that multiphase solid models can simulate real values depending on more accurate crack patterns that could result in failure. It was also reported that with the development of simulation tools, experiments can be supported by simulations, used to verify performance and determine optimum design parameters in a relatively short time. Some equations for density, compressive strength and elastic modulus developed by different researchers are demonstrated in Tables 9–11, respectively.

Table 9. Equations for density.

Reference	Equations	Remarks
[103]	$\gamma_{dry} = 0.86\gamma_{cast} - 55.07$	Fly ash–cement ratio (F/C = 0–4), casting density range of 700–1500 kg/m^3
[104]	Dry density = (Wc + 0.2 Wc)/V_{batch}	Wc = weight of cement V_{batch} = volume of batch
[105]	Dry density = 1.2 C + A	C and A are weight of cement and aggregate in kg per cubic meter of concrete
[106]	D = (Mc − Mm)/Vm	D is the dry bulk density of concrete (Ib/ft^3), Mc is the weight of the measure holding the concrete, Mm is the weight of the empty concrete measure, Vm is the volume of the measure, which is usually about 0.25 ft^3 for a pressure meter base.

Table 10. Equations for compressive strength.

Reference	Remarks	Equations
[107]	P_{cr} = the critical porosity corresponding to zero strength, K_s = a constant, "Schiller's equation"	$f_{cc} = K_s \ln(P_{cr}/p)$
[108]	f_c = compressive strength of the cement paste, A = air content	$f_{cc} = 1.048\, f_c(1 - A)^{2.793}$
[95]	f_c = compressive strength (MPa); c, w, a = absolute volumetric ratios of cement, water and air; K = is used as a constant.	$f_c = Kcc + a^2 + w$
[43]	f_c = cube compressive strength (MPa), t = time since casting (days), w/c = effective water/cement ratio, f_{cc} = compressive strength of foamed concrete, α_b = binder ratio	$f_{cc} = 1.172\, f_c {\alpha_b}^{3.7}$ $f_c(t; w/c) = 88.04 + 6.569 \ln(t) - 130.5\, w/c$
[96]	σ_y = compressive strength; σ_0 = theoretical strength of paste with zero porosity; b = power exponent; d_c = concrete density; k = w/c (by weight); ρ_c = specific gravity of cement; and γ_w = unit weight of water.	$\sigma_y = \sigma_0 \left(\frac{d_c}{1+k}\right)^b \left(\frac{1+0.20\rho_c}{\rho_c \gamma_w}\right)^b$

Table 11. Equations used for elastic modulus.

Reference	Remarks	Equations
[28]	Sand as fine aggregate	$E = 0.42\ f_c^{1.18}$
	Fly ash as fine aggregate	$E = 0.99\ f_c^{0.67}$
[109]	E (kN/mm^2), f_{cu} (N/mm^2) and ρ (kg/m^3) are the estimated elastic modulus, cubic compressive strength, and air-dry density, respectively.	$E = (\rho/2400)^2 \times (f_{cu})^{1/3}9.1$
[110]	Density from 200 to 800 kg/m^3	$E = 5.31\ W - 853$
[111]	Pauw's equation	$E = 33\ W^{1.5}\ \sqrt{f_c}$

6. Durability of Foam Concrete

6.1. Freeze–Thaw Resistance

ASTM C666 determines the ability of normal weight concrete to resist rapid freezing and thawing cycles and produces microcracking and scaling type failure while conducting on foam concrete [30,112]. Tikalsky et al. [30] developed a modified freeze–thaw test procedure based on ASTM C666. Compressive strength, initial penetration depth, absorption rate variables have important effects on the production of freeze–thaw resistant foam concrete. It was reported that density and permeability are not important variables.

The water entering into the concrete expands during the freezing event and creates stresses. The porous structure of foam concrete provides good freeze–thaw resistance by providing additional space where water can expand [50]. Foam concretes generally offer good FT resistance compared to non-aerated concrete. Shon et al. [78] showed, as a result of their work, that foam concretes with high porosity did not always result in higher FT resistance. It was found that the FT resistance of foam concrete is affected more than the size of the air void, and the number of air voids smaller than 300 µm was reported to play a critical role in reducing FT damage in foam concrete. Since the number of freeze–thaw cycles increases, mass losses increase and spallings occur on the surface of foam concrete samples [23]. The type of foam used in foam concrete has an effect on mass loss and strength loss [36]. Density difference affects the FT resistance of foam concretes. It was reported that low density foam concretes experience more expansion and high loss of mass and strength. This situation was attributed to the larger and interconnected pore structure of low-density foam concretes. Such a pore structure will allow more water intake into the concrete, causing the foam concrete to show lower resistance to FT [11].

6.2. Elevated Temperature Resistance

When exposed to high temperatures, foamed concrete experiences extreme shrinkage due to high evaporation rates. However, compared to normal concrete, foam concrete has an acceptable FR [57]. FR is related to the changes in the mechanical properties of foam concrete when exposed to high temperatures [3]. Generally, the compressive strength feature of foam concrete increases up to 400 °C. The reason is that high temperature stimulates the reactivity of the binders. However, the strength gradually decreases afterwards [17,18,24].

As the temperature that foam concrete is exposed to increases, hardness loss occurs. It was reported that this loss of hardness starts after 90 °C regardless of the density [80]. It was reported that foam concretes with a density of 950 kg/m^3 can withstand fire up to 3.5 h and concrete with a density of 1200 kg/m^3 for up to 2 h [3]. Cavity structures help to reduce the effects of high temperature on foam concrete [94]. The pore structure of foam concrete is generally related to density, and it was reported that it is not affected by high temperatures. For this reason, the loss of strength at high temperatures is caused by the changing chemical components of foam concrete [80].

Mineral additives and aggregates affect the properties of foam concrete after exposure to high temperatures. Pozzolanic additives can provide an increase in strength with an increase in temperature. The compressive strength increased after the foam concrete containing RHA and WMP was exposed to 200–400 °C. At temperatures above 400 °C, due to water loss in crystallization, changes in the $Ca(OH)_2$ content as well as changes in morphology and formation of micro cracks cause a decrease in compressive strength [18]. The thermal resistance of geopolymer foam concrete is evaluated on the changes in compressive strength and volume after exposure to high temperatures. Zhang et al. [17] worked entirely on foam concretes produced with a combination of FA and FA-slag. A 100% increase in compressive strength up to 800 °C was experienced in geopolymer foam concrete (GFC) with FA. However, in GFCs prepared with FA–slag combination, an increase in compressive strength up to 100 °C was observed, and then the compressive strength decreased. Because it is much more degraded with the loss of chemically bound water than gels rich in calcium formed by the FA–slag combination.

Cracks occur in foam concrete as the exposed temperature increases. It was reported that cracks occur on the foam concrete surface after 400 °C and increase with the increase in temperature. At the same time, the cracks seen in foam concretes with high density are more numerous [14]. Moreover, the methods of cooling the samples (with air or water) affect the formation of cracks. It was observed that the slowly cooling (by air) samples had a greater tendency to crack. An increase in the amount of cracks increases the loss of strength [18].

6.3. Acoustic

Acoustic properties are the least studied ones for foam concrete. Factors such as the foam content, the amount, size and distribution of pores and the inclusion of their uniformity can affect the sound insulation of foam concrete. Compared to normal concrete wall, foamed concrete cellular walls transmit sound frequency with up to 3% higher value, and foamed concrete has 10 times higher sound absorption rate than dense concrete [57]. It was reported that sound absorption increases at 800–1600 Hz in foam concrete containing FA. This was attributed to the altered pore properties with the addition of FA. In addition, the increase in foam dosage has less of an effect at low frequencies. Medium-frequency foam concretes (600–1000 Hz) were reported to be a more efficient material [17].

Zhua et al. [17] reported that thin GFC samples of 20–25 mm exhibit an impressive acoustic absorption rate (α = 0.7–1.0) in the low frequency region of 40–150 Hz, and that the average sound absorption of the GFC is better than dense concrete. Mastali et al. [59] showed that alkali active slag foam concretes developed using 25–35% foam content in their study exhibited excellent maximum acoustic absorption coefficients (0.8–1) in medium- and high-frequency regions. It was reported that there is a linear correlation between the density and acoustic properties of the alkali active slag foam concretes used in the study. In other words, the acoustic properties are improved by decreasing the density.

6.4. Thermal Conductivity

The porosity and density of concrete are the two main parameters affecting the thermal conductivity value [51]. The change in the foam ratio affects the dry density, the change in the dry density affects the thermal conductivity [39]. As the dry density increases, the thermal conductivity increases.

Zhang et al. [17], in their study investigating the mechanical, thermal insulation and acoustic properties of geopolymer foam concrete, determined that when the dry density increased from 585 to 1370 kg/m^3, thermal conductivity increased from 0.15 to 0.48 W/mK. The amount of porosity increases as the dry density decreases. Increase in porosity decreases thermal conductivity. Similarly, the w/c increase decreases thermal conductivity by increasing porosity [86]. In other words, thermal conductivity increases with dry density. GFC was reported to have better thermal insulation properties than Portland cement foam concrete (same density and/or strength).

Thermal conductivity varies depending on the type of cement used and the foaming gas. The lower the thermal conductivity of the cement and the foaming gas used, the lower the thermal conductivity of the foam concrete [37,39,40]. Li et al. [37] studied the effect of foaming gas and cement type on the thermal conductivity of foamed concrete. For the research, foam concrete was prepared using four different foaming gases (air, hydrogen, oxygen, carbon dioxide) and three different cement types (MPC, SAC, OPC). The thermal conductivity of MPC-based foam concrete was higher than that of other cements. The thermal conductivity of foamed concrete using hydrogen foaming gas was the highest, and the one using carbon dioxide foaming gas was the lowest. The reason for this is that carbon dioxide gas has a much lower thermal conductivity (0.014 W/mK) than the ones for atmospheric (0.025 W/mK) and ammonia gasses (0.025 W/mK). Therefore, the use of carbon dioxide foaming gas is an effective method to improve thermal insulation [41]. Partial (30%) replacement of FA with cement helped to reduce the heat of hydration. The use of lightweight aggregates, with low particle density, among air voids artificially inserted into the mortar matrix, was advantageous in reducing thermal conductivity [1]. In the study performed by Gencel et al. [51], the thermal conductivity of foam concrete decreased with the RCA. This is thanks to the increased porosity with the use of RCA. The increase in porosity decreased thermal conductivity. Likewise, thermal conductivity decreased when RCA geopolymer was used in foam concrete. The uniform and increased amount of air void with the use of RCA may have provided this [19]. The SF improves the opening distribution, making the pores more uniform and closed circular, which increases the insulation performance [90]. The use of coir fiber reduced the thermal conductivity of foam concrete. Coir fiber has low thermal conductivity thanks to its high heat resistance. This can be shown as another example proving that materials with low thermal conductivity reduce the thermal conductivity of foam concrete. In addition, the formation of uniform air voids in concrete thanks to fiber addition is another factor that reduces thermal conductivity [60]. The thermal conductivity results of different studies are given in Table 12.

Table 12. Thermal conductivity results of different studies.

References	Cement and Additives	Foaming Material	Density (kg/m^3)	Thermal Conductivity (W/mK)
[46]	PC + GGBFS	H_2O_2	150–300 (dry)	0.05–0.070
[40]	MPC	H_2O_2	300–1000 (dry)	0.136–0.347
[86]	PC + FA	Protein	975–1132 (bulk)	0.225–0.264
[26]	PC + FA	Protein	970–1307 (dry)	0.24
[113]	PC + FA	Synthetic	860–1245 (dry)	0.021–0.035
[114]	PC + FA + SF	Synthetic	1100–1600 (dry)	0.40–0.57
[115]	PC	Protein	650–1200 (dry)	0.23–0.39
[17]	GFC	-	585–1370	0.15–0.48
[51]	PC + FA	Protein	594–605 (Unit weight)	0.154–0.162
[9]	PC + BT	-	300–600	0.06–0.15

7. Microstructure Investigations of Foam Concretes

In this section, the effects of the contents of foam concrete on the microstructure will be shown. In the SEM image given in Figure 3, the w/c ratios and the effect of the added additives are compared. The foam concrete in the image on the left has a w/c ratio of 0.60 and is unadulterated. The one on the right is foam concrete produced with a w/c ratio of 0.35 using a superplasticizer and micro silica. The use of micro silica and superplasticizer helped to create a more robust structure [116].

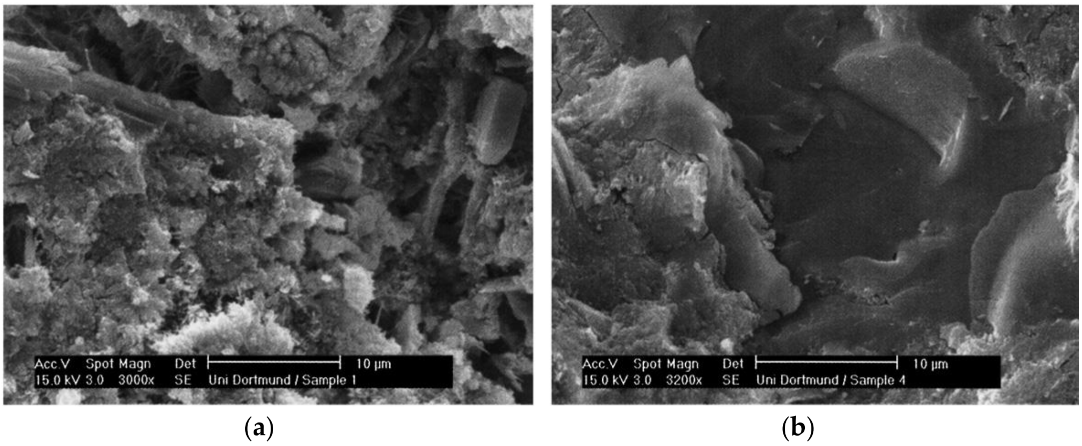


Figure 3. Microstructure of two foam concrete; (**a**) w/c = 0.60, containing no microsilica content; (**b**): w/c ratio = 0.35, with 10% microsilica content. Reprinted/adapted with permission from Ref. [116]. 2009, Elsevier Science &Technology Journals.

The effect of the increase in the w/c ratio on the pore structure of foam concrete is given in Figure 4. The increase in w/c increased the pore diameter and made the pores more rounded. The reason for this can be shown as the decrease in viscosity with the increase in the amount of water and thus the difficulty of maintaining the bubbles. As a result, bubbles can easily coalesce, and larger pores can be formed [72].

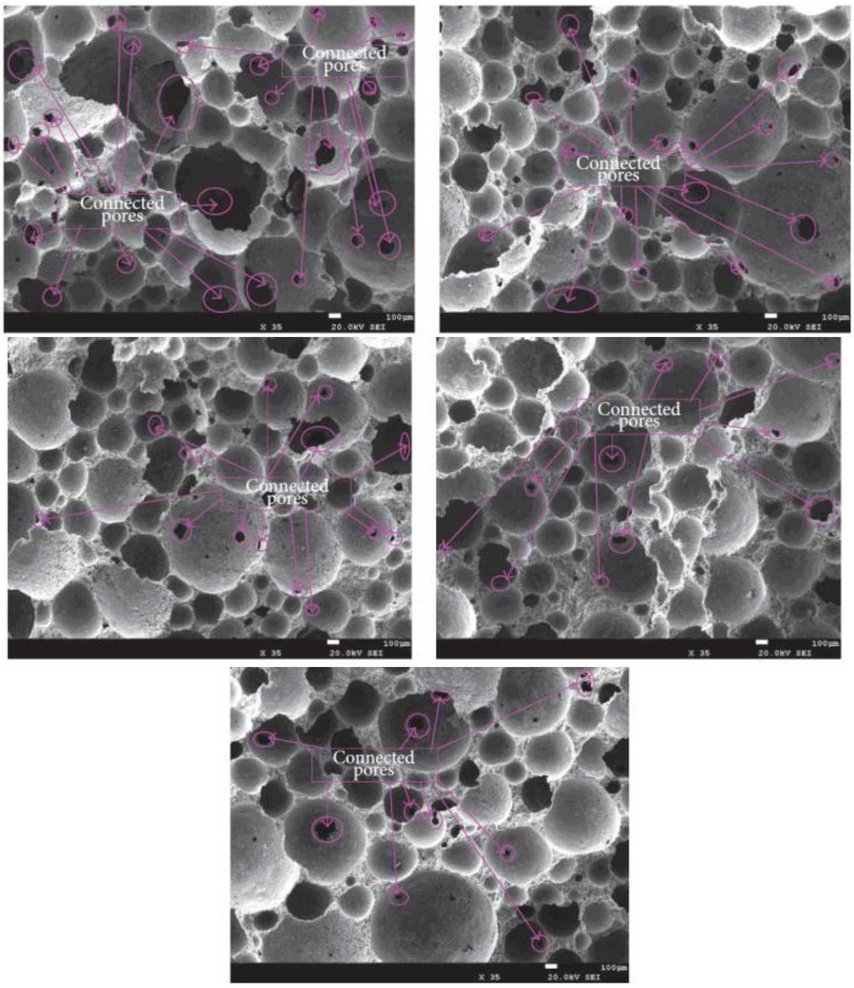


Figure 4. The effect of change in w/c ratio on pore structure [72].

The microstructure of foam concrete is given in Figure 5 when the WMP replaced silica sand and RHA replaced cement. When the sample without additive (F40R0M0) is considered, it is seen that the cement and silica sand particles form a compact structure with CSH. With the addition of marble waste (F40R0M25), there appears to be an increase in the amount of CSH. This is due to the presence of SiO_2 in the structure of the marble waste. The presence of RHA (F40R10M0) has extended the size of CSH. With the presence of both (F80R20M50), foam concrete had larger CSH gels [18].

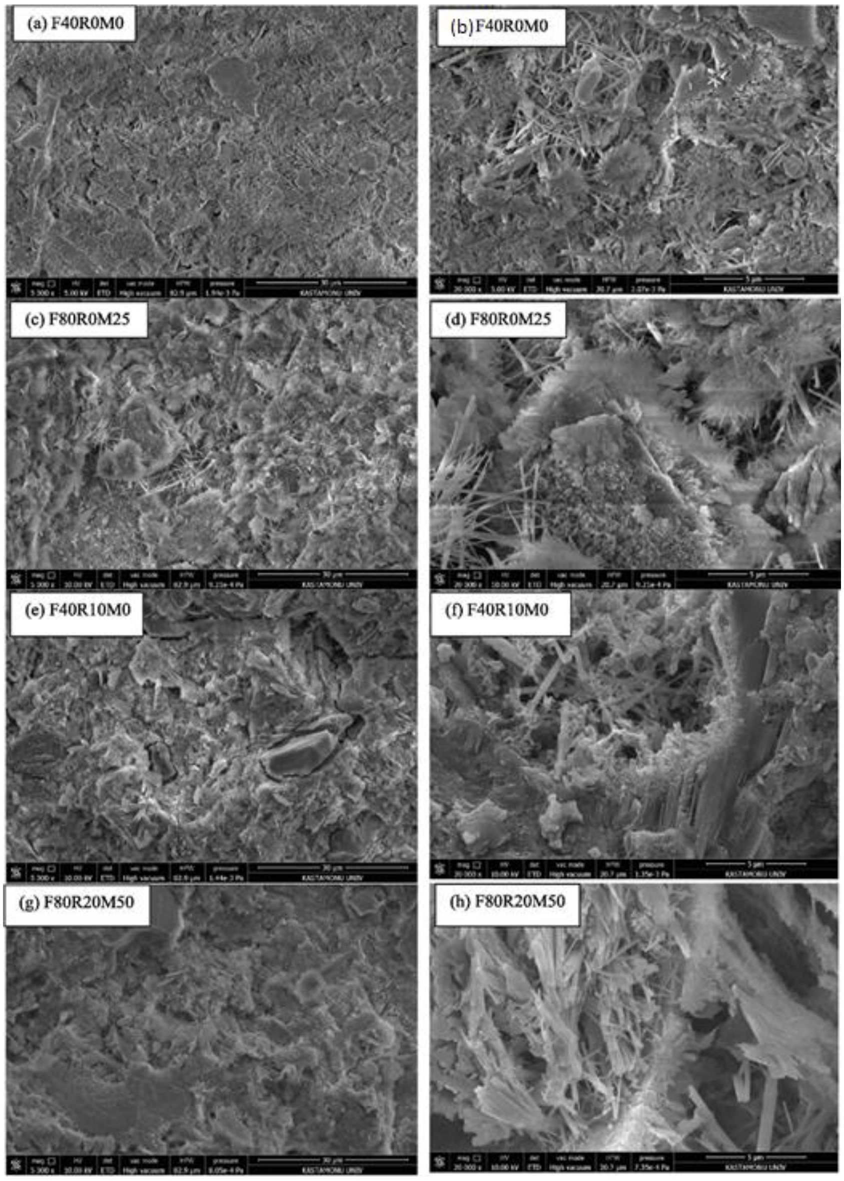


Figure 5. SEM images of foam concrete samples (F: foam content, R: rice husk ash, M: waste marble powder). Reprinted/adapted with permission from Ref. [18]. 2021, Elsevier Science &Technology Journals.

Looking at the SEM images (Figure 6), there was no significant difference in the microstructure of the paste with the use of CBP, up to 7.5%. The microstructure of the paste with up to 30% CBP was looser than the control group. The reason for this can be shown to decrease the hydration products in the cake significantly. Since CBP has higher silica content and lower calcium content than cement, the amount of calcium decreases, and the amount of silica increases as the ratio increases [22].

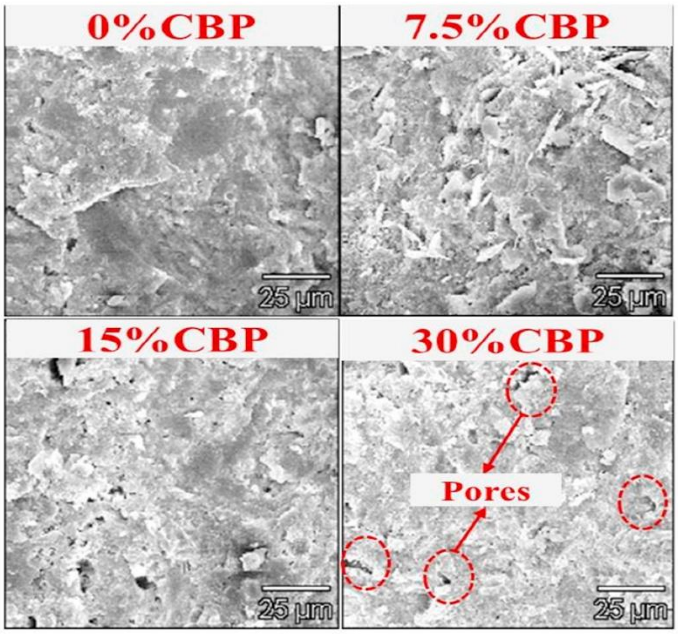


Figure 6. SEM images with various CBP content. Reprinted/adapted with permission from Ref. [22]. 2020, Elsevier Science &Technology Journals.

Figure 7 shows SEM images of foam concrete samples with and without FA. For both samples, MAP products can be observed as well crystallized crystals. When looking at (c) and (d), some FA particles are seen. Some large pores are observed in (a) and (b). FA can improve the pore structure by filling the pores. This property may contribute to the improvement in the strength and thermal insulation of FA [41].

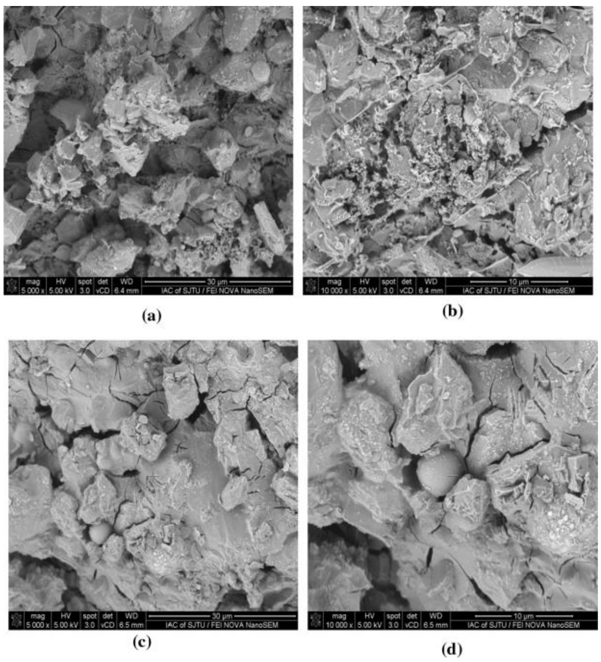
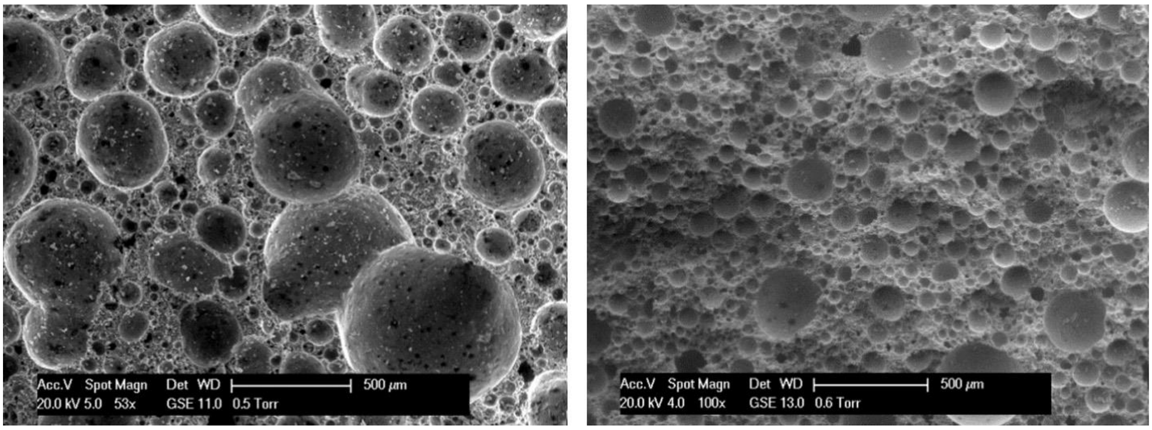


Figure 7. SEM photographs: (**a**,**b**) for the sample number 6; (**c**,**d**) for sample number 11. Reprinted/adapted with permission from Ref. [41]. 2017, Elsevier Science &Technology Journals.

In Figure 8, SEM images of foamed concretes with densities of 500 kg/m^3 and 1000 kg/m^3, respectively, are given. In concretes with high air content, air pockets tend to become closer to each other, causing larger air pockets. The size of the air voids increased because there was not enough paste to prevent the joining of the air voids, which were formed by the decrease in the paste content and the increase in the amount of foam. Concrete with higher air content tends to cause larger air pockets due to the proximity of air pockets. This leads to a higher incidence of void fusion, which creates larger irregular air pockets. This observation is more important in concrete with a plastic density of less than 900 kg/m^3, where the corresponding foam content is 52%. The average air void size increases significantly for paste content less than 48% since the cement paste content is not enough to prevent air voids from coalescing [117].



(**a**) (**b**)

Figure 8. SEM images of foamed concrete ((**a**): concrete density = 500 kg/m^3, (**b**): concrete density = 1000 kg/m^3). Reprinted/adapted with permission from Ref. [117]. 2013, Elsevier Science &Technology Journals.

SEM images of foam concrete prepared using different types of foaming agents (synthetic surfactant (SS), vegetable surfactant (PS), and animal surfactant (AS)) are given in Figure 9. The SS foaming agent contains a nanoparticle stabilizer. This stabilizer is beneficial for its high stability and strength. It is seen that the pore walls of foam concrete prepared using SS are thicker than those of AS and PS. The largest pore diameters of AS, PS and SS are 860 µm, 1162 µm and 517 µm, respectively. The pore size of SS foam concrete is smaller, and the number of connections is fewer. In this way, foam concrete prepared with SS shows higher compressive strength, lower water absorption and stronger frost resistance [36].

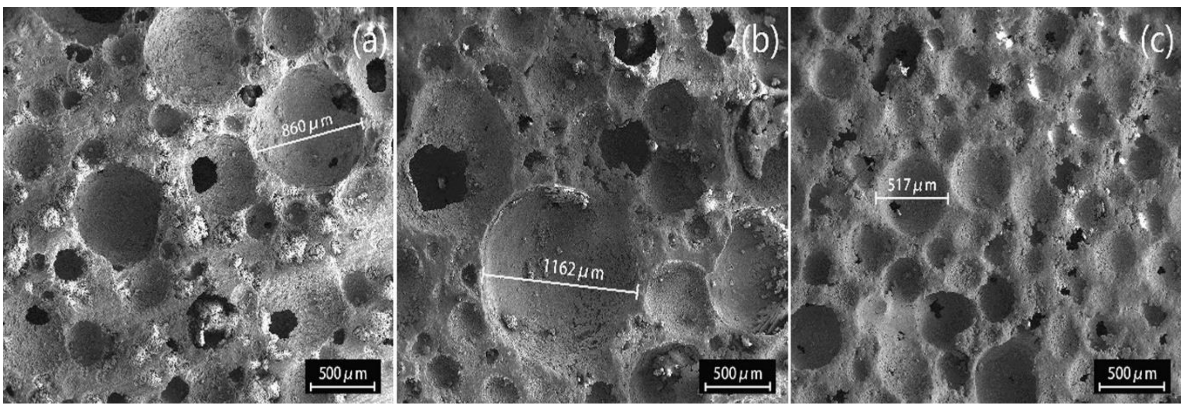


Figure 9. SEM images of foamed concrete at 100×: (**a**) AS, (**b**) PS, (**c**) SS. Reprinted/adapted with permission from Ref. [36]. 2018, Elsevier Science &Technology Journals.

SEM images of synthetic- and protein-based foam concretes are given in Figure 10. Protein-based foam concrete, shown in Figure 10a, has smaller pore size and several large randomly distributed air pockets. The pore diameter is varied mostly up to 500 microns. The pore size distribution reached up to 650 microns simultaneously in Figure 10b for synthetic-based foamed concrete. In addition, in synthetic-based foamed concrete, there is a visible consolidation and deterioration in the pores [20].

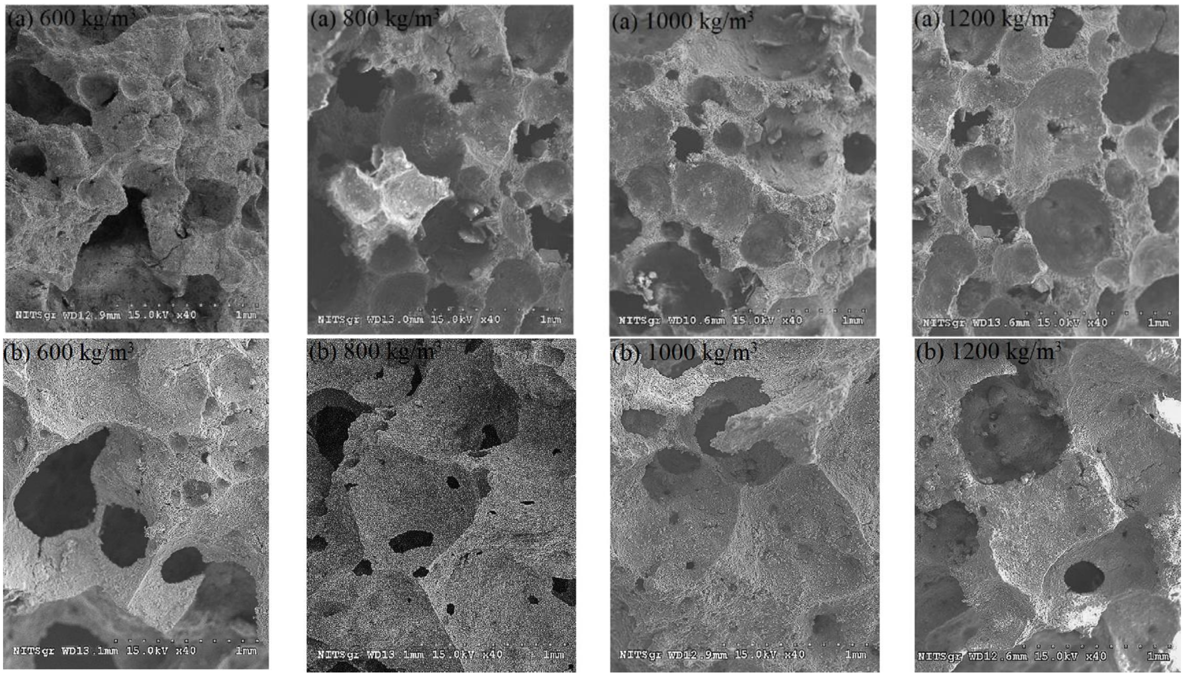


Figure 10. Microscopic images: (**a**) protein-based foam concrete, (**b**) synthetic-based foamed concrete. Reprinted/adapted with permission from Ref. [20]. 2021, Elsevier Science &Technology Journals.

SEM images of foam concrete samples exposed to 800 °C are given in Figure 11. Chemically bound water and hydration products in concrete appear to be decomposing. Microcracks occurred due to the dissociated calcium silicate phases [18].

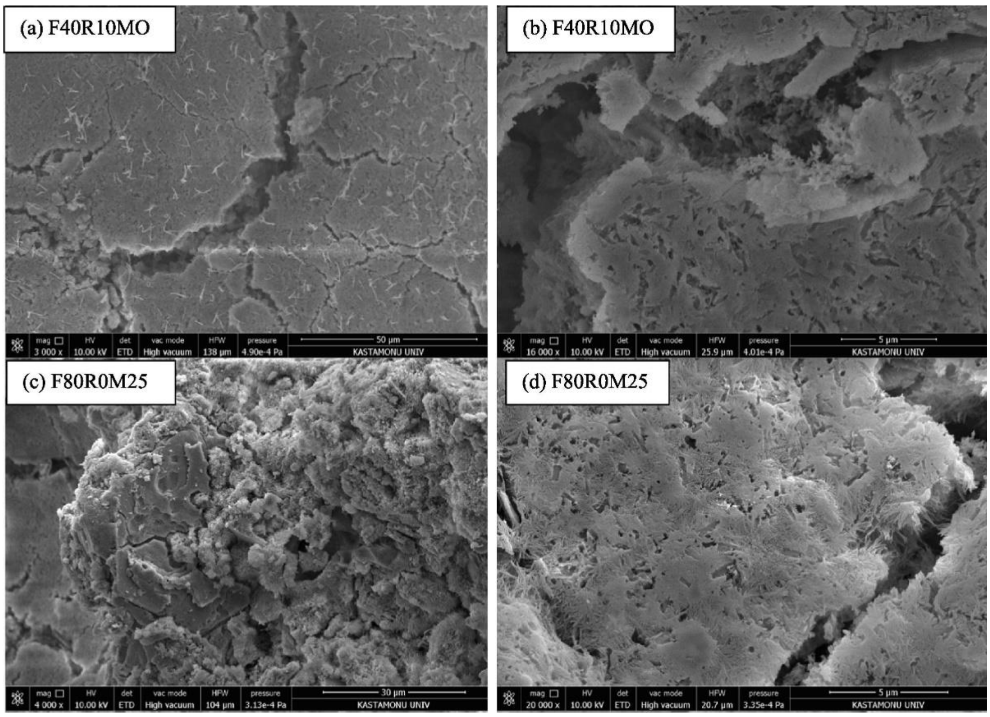


Figure 11. SEM images of foam concrete samples exposed to 800 °C. Reprinted/adapted with permission from Ref. [18]. 2021, Elsevier Science &Technology Journals.

8. Conclusions

Today, understanding the properties of foam concrete is of interest to researchers, and many studies focusing on different properties of foam concrete are being conducted. The properties of foam concrete vary depending on many factors. Factors such as foam type, cement type, mineral additives, aggregate type, and the properties of the air spaces created directly affect the strength, fresh and hardened properties of foam concrete. This article examines the materials that make up foam concrete, their fresh and hardened properties, and the changes in their strength and microstructure.

Based on the review presented in this study, the following conclusions can be drawn:

1. Foam stability affects the strength properties of foam concrete. The foam stability affects properties, such as the selected foaming agent, aggregate, and water amount used.
2. The increase in the foam volume significantly reduces the consistency, and the increased air voids overlap and increase the amount of combined pore. The distance between the air voids, pore structure, and pore size affect strength.
3. The increase in the amount of foam also affects the density of the foam concrete.
4. An increase in the amount of paste increases the amount of drying shrinkage.
5. The thermal conductivity coefficients of the materials preferred in foam concrete production affect the thermal conductivity of the foam concrete.
6. The use of wastes, such as fly ash as a filler, has a positive effect on strength properties. However, due to its pozzolanic properties, it provides late strength gain. This may cause a decrease in strength, especially at early ages, when used as cement replacement.

To better understand the fresh state properties of foam concrete, the factors affecting the fresh state properties should be examined in future studies. In addition, the effects of the materials that make up the foam concrete on the durability properties require further research to be better understood. In particular, the evaluation of waste aggregates and the effects of the use of various aggregates should be included in this research. Models should continue to be developed in order to be able to prepare mixtures easily and to produce the aimed foam concretes. In this way, the mechanical and strength properties of foam concrete can be determined faster and easier, and researchers can make reliable predictions. Acoustic foam concrete is the least researched subject, and in this respect, it is necessary to focus more on acoustic properties.

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Nomenclature

ACP	Acoustic Properties
ANN	Artificial Neural Network
AS	Animal Surfactant
AVC	Air Void Content
BF	Basalt Fiber
BFS	Blast Furnace Slag
BT	Bentonite
CBP	Clay Brick Powder
CDW	Construction and Demolition Waste
CTAB	Cetyltrimethyl Ammonium Bromide
DS	Drying Shrinkage
EPS	Expanded Polystyrene
EVP	Expanded vermiculite powder

FA	Fly Ash
FC	Flow Cone
FR	Fire Resistance
FT	Freeze-Thaw
FUW	Fresh Unit Weight
GFC	Geopolymer Foam Concrete
HP	Hydrolyzed protein
HUW	Hardened Unit Weight
MAP	$MgNH_4PO_4 \cdot 6H_2O$
MC	Marsh Cone
MPC	Magnesium Phosphate Cement
MST	Mechanical Strength
MT	Metakaolin
NAC	Sodium Bicarbonate
OPC	Ordinary Portland Cement
PC	Portland Cement
PRS	Porosity
PS	Plant Surfactant
PVA	Polyvinyl alcohol
QL	Quick Lime
RCA	Recycled Coarse aggregate
RGP	Recycled Glass Powder
RHA	Rice Husk Ash
RP	Rubber Powder
RS	River Sediment
RT	Rheology Test
SA	Set Accelerator
SAC	Sulfoaluminate Cement
SEM	Scanning Electron Microscopy
SF	Silica Fume
SS	Synthetic Surfactant
SLS	Sodium Lauryl Sulfate
SND	Sand
SP	Slag Powder
THP	Thermal Properties
WP	Water Absorption
WMP	Waste Marble Powder
WPC	White Portland Cement

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