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Foam Concrete: A Review

Dr. Kiran Bhaskar
Associate Professor, Department of Civil Engineering, Navkis College of Engineering, Hassan, Karnataka, India

Abstract: Foam concrete has the potential of being an alternative to ordinary concrete, as it reduces dead loads on the structure and foundation, contributes to energy conservation, and lowers the cost of production and labour cost during the construction and transportation. Presently the emerging trend is the use of foam concrete, which is a lightweight concrete having more strength-to-weight ratio with density varying from 300 to 2000 kg/m^3. This reduces the dead load on the structure, cost of production and labour cost involved during the construction and transportation. Also, the large number of pores in the foamed concrete reduces the thermal and sound absorption, thus making the structure appropriate for all climatic conditions. The paper outlines a review of foamed concrete in terms of its definitions & classifications, materials, mix design, production of foamed concrete, properties of foamed concrete such as workability, density, compressive strength, porosity, fire resistance, shrinkage, water absorption, permeability. Apart from this, the paper outlines various applications of foam concrete.
Keywords: foam concrete, mix design, workability, density, porosity, compressive strength

I. INTRODUCTION

About two thousand years ago, the Romans were producing concrete mixture comprising of small gravel and coarse sand combining together with water and hot lime. They shortly discovered that by incorporating animal blood into the mix and agitating it, small air bubbles were created making the mix more workable and durable. There is also confirmation that the Egyptians used a similar technology over 5000 years ago (Aldrige, 2005). No remarkable progress was made with this category of aerated cementitious materials until the early 1900s, when the production of highly air-entrained cement based composites began to be commercially explored in Scandinavia (Sweden and Denmark) and the first cement-based foams in the present era was patented in 1923 by Axel Eriksson (Beningfield, Gaimster, & Griffin, 2005; Jones & McCarthy, 2005b). In that application, the entrained gas was produced by the generation of hydrogen gas (using powdered aluminium or hydrogen peroxide) in a slurry mix made alkaline by the inclusion of Portland cement and, at times, lime. Over the past century since that development, its usage has grown worldwide and considerable advances have been made in the production technology.

Cement-based foams are now produced by introducing air in one of three ways: (1) by the addition of relatively large amounts of powerful air-entraining agents; (2) by the addition of foaming agents; or (3) through chemical admixtures that release gas bubbles during the mixing process (Beningfield et al., 2005; Goual, Bali, de Barquin, Dheilly, & Queneudec, 2006). Accordingly, these low-density cement based composites are classified as (1) highly air-entrained concrete, (2) foamed concrete, and (3) aerated concrete.

Because of its cellular microstructure, these types of cementitious composites are in general called cellular concrete. This paper deals with the production and properties of foamed concrete.

II. DEFINITIONS AND CLASSIFICATIONS

According to ACI 523.2R the material, which is commonly referred to as cellular or aerated concrete, may be defined as (ACI 523.2R-96, 1996), *A lightweight product consisting of Portland cement and/or lime with siliceous fine material, including sand, slag, or fly ash, and mixed with water to form a paste that has a homogeneous void or cell structure. The cellular structure is attained essentially by the inclusion of macroscopic voids resulting from a gas-releasing chemical reaction or the mechanical incorporation of air or other gases (autoclave curing is usually employed).*

The British Cement Association has defined foamed concrete as "a lightweight material produced by incorporating a preformed foam, into a base mix of cement paste or mortar, using a standard or proprietary mixing plant." The entrapped air bubbles reduce the density of the base mix and have a strong plasticizing effect on it (British Cement Association, 1994).

Typically, the mixture composition in foamed concrete is made up of cementitious binder, sand, water, and entrained air, so that it contains no coarse aggregate. In composition, it is thus perhaps more closely related to paste or mortar. Some researchers refer to it as a highly air-entrained cement sand slurry (Beningfield et al., 2005). Cox and van Dijk (2002) and Cox (2005) further state that this product is not created by foaming ordinary concrete. Rather, the pores are introduced by agitating air with a foaming agent diluted with water, thus creating a mechanically manufactured foam. This foam is then carefully blended in with the cement slurry or the base mix (Cox, 2005). Alternatively, Kearsley and Mostert (2005a, 2005b) have defined it as a cementitious material where in a minimum of 20% of the volume consists of foam that is entrained into the plastic mortar.

III. MATERIALS

As mentioned before, foamed concrete consists principally of Portland cement, water, a foaming agent, and/or other fine materials. In addition, cement replacing materials, mineral, and chemical admixtures have been successfully used in foamed concrete. As suggested by ACI 523.1R-06 (2006), all the admixtures must be compatible with the stable foam within a specific mixture.

A. Portland Cement

Portland cement is the main cementitious component of foamed concrete. It has been used at dosages varying from as high as 1400 kg/m3 to as low as 75 kg/m3 but in practice, usually between 300 and 500 kg/m3 (ACI 523.1R-06, 2006; British Cement Association, 1994; Jones & McCarthy, 2005b; Papayianni & Milud, 2005). In addition to normal Portland cement, rapid hardening Portland cement, high alumina cement and calcium sulfoaluminate cements have also been used in foamed concrete to reduce its setting time and improve the early strength (Jones & McCarthy, 2005b). Using geocements and alkaline Portland cement is reported to improve the fire resistance of foamed concrete (Krivenko, Kovalchuk, & Kovalchuk, 2005).

B. Mineral Admixtures

Depending on the application, cement replacing materials such as fly ash (FA), ground granulated blast-furnace slag (GGBFS), solid wastes, and silica fume (SF) have been added to foamed concrete (Aldrige, 2005; Jones & McCarthy, 2005b; Kearsley & Mostert, 2005b; Kearsley & Wainwright, 2001b; Kearsley, 1996; Kearsley, 1999; Lee & Hung, 2005; Papayianni & Milud, 2005). In addition, Proshin, Beregovoi, Beregovoi, and Eremkin (2005) used mineral admixtures in the form of fine-crushed carbonate or quartz sands. Similarly, Lee and Hung (2005) investigated the use of solid wastes such as rice husk (as a pozzolanic admixture), expanded polystyrene (as a light-weight aggregate), and paper sludge (which contains fragments of paper fibers that serve as reinforcement) in foamed concrete.

Cement may be successfully replaced with FA (up to 80%) and several studies report its effect on the properties of foamed concrete (Kearsley & Wainwright, 2001b; Kearsley, 1999; Papayianni & Milud, 2005). Further, Kearsley and Wainwright (2001b) examined the effect of incorporating unclassified ash, so called by the South African Bureau of Standards (SABS) 1491: Part II (1989), since approximately 40% of the particles have a particle size exceeding 45 µm [this criterion is similar to ASTM C618-05, which limits the maximum amount of FA retained when wet-sieved on the 45 µm (no. 325) sieve to 34% (ASTM C618-05)]. Their research indicates that large volumes of FA can be used in foamed concrete. Although the high ash content results in a decrease in the early strength, the long-term strength was improved by replacing up to 75% of cement with FA. The trends observed for the classified ash on the one hand, where according to SABS 1491: Part II (1989), approximately 12.5% of the particles have a particle size less than 45 µm, and the unclassified ash on the other were similar (Kearsley & Mostert, 2005b; Kearsley & Wainwright, 2002a; Kearsley, 1999).

GGBFS has also been added to Portland cement at levels between 30% and 50% by cement mass while SF has been incorporated into foamed concrete at up to 20% by mass of cement and was found to be effective in improving the compressive strength of the mixtures with low percentage of foam (up to 30%) without affecting the stability of the air-void system. Whereas mixtures with a high volume of foam (.30%) showed no effect of SF (Jones & McCarthy, 2005b; Kearsley, 1996), adding SF leads to a reduction in free water with attendant benefits to thermal conductivity (Batool & Bindiganavile, 2017). When using admixtures, particular care must be given to factors such as economy, consistency, mix stability, and contribution to strength in deciding their suitability. For instance, the use of high volume of FA results in the destabilization of the mix, but it can be prevented by using foam stabilizers. Also, a FA with a high loss on ignition (i.e., high carbon content) may adversely affect the preformed foam by causing an increase in its density and consequent loss of yield (Jones & McCarthy, 2006).

C. Aggregates

In general, coarse aggregate is not used in the production of foamed concrete. On the other hand, the use of fine aggregates with a maximum particle size of up to 5 mm is recommended. However, the fine aggregate fraction can be partially or fully replaced with recycled or secondary materials, including FA, lime, chalk, crushed concrete, granite dust, recycled glass, expanded polystyrene granules, and those arising from demolition (Jones & McCarthy, 2005b, 2006; Kearsley, 1996; Lee & Hung, 2005). Of course, the aggregate phase may be replaced with more air bubbles. Thus, it is also not uncommon to completely exclude the fine aggregate fraction.

D. Foaming Agents

There are two principal methods of producing foamed concrete, namely, (1) the prefoamed method and (2) the mixing foam method (Aldrige, 2005; Nambiar & Ramamurthy, 2007). The foams that are used may be either synthetic or protein based and are available from proprietary sources. As mentioned earlier, the Egyptians and the Romans used animal blood to entrain air into concrete. These days, refined animal products form the basis for protein-based foams. On the other hand, synthetic foams are made of amine and amine oxides, naphthalene sulfonate formaldehyde condensates, etc. Some of these products can contain one or more substances classified as dangerous or hazardous to the environment. Hence caution must be exercised when using these products, especially those based on formaldehyde condensates, butyl carbitol, and glycol ethers (Timbrell, 2007). The protein based foaming agents result in stronger and a more closed-cell bubble structure while the synthetic types yield greater expansion and thus lower density (ACI 523.2R-96, 1996; Tikalsky, Pospisil, & MacDonald, 2004). In addition, protein based foams permit the inclusion of greater amounts of air and also provide a more stable air-void network (Beningfield, Gaimster, & Griffin, 2005). Note that the foam itself has no chemical action in concrete.

The preformed foam that is blended with the base materials to produce foamed concrete can be divided into two categories: wet foam and dry foam. The wet foam is produced by spraying a solution of the foaming agent (usually synthetic) and water over a fine mesh that results in a network of bubbles ranging from 2 to 5 mm in diameter. The wet foam has a large loose bubble structure and although relatively stable; it is not recommended for the production of low-density (below 1100 kg/m3) foamed concrete. It is also not suitable for pumping over long distances or for pouring to great depths.

The dry foam is similar in appearance to shaving foam and has a bubble size distribution much smaller than wet foam (less than 1 mm) and is extremely stable. While synthetic foams are easier to handle and can be stored longer, they are less susceptible to extremes of temperature. In addition, they are less expensive and they require less energy to produce. On the other hand, foams based on animal protein can produce stronger concretes. This is because the foaming agents based on animal protein possess the ability to take on water and hold it within the protein

structure. During the cement hydration process, this water is released from the foam and is readily available to the cement particles. This results in a network of hydration products around the air bubbles ensuring a strong microstructure (Aldrige, 2005). ASTM C796-04 (2004) and ASTM C869-91 (2006) introduce standard test methods and standard specifications, respectively, for foaming agents used in the making of preformed foam for cellular concrete.

IV. MIX DESIGN

There is no standard method for designing a foamed concrete mixture. The design philosophy differs from that for regular concrete in that the mixture proportions are chosen, not only for a specified compressive strength, but also for a specified density.

As seen in normal concrete, the greater the air content, the lower the strength. As expected therefore, foamed concrete has characteristically a much lower strength than normal concrete does. Again, as with normal concrete, the strength of foamed concrete is related to its cement and water content. However, in addition, the type and the content of the foaming agent have a marked effect on the properties of both the fresh and the hardened materials. Using mineral admixtures such as FA, GGBFS, SF, and metakaolin (MK) will also result in a significant change in both fresh and hardened properties (Aldrige, 2005; Jones & McCarthy, 2005b; Kearsley & Mostert, 2005b; Kearsley & Wainwright, 2001b, 2002a; Lee & Hung, 2005; Papayianni & Milud, 2005). Furthermore, just as the water-cement (w/c) ratio holds relevance to normal concrete technology, some foam concrete mixes are designed based on the aggregate-cement ratio and/or the sand-cement ratio (s/c) (Hamidah, Azmi, Ruslan, Kartini, & Fadhil, 2005; Jones & McCarthy, 2005b; Wee, Babu, Tamilselvan, & Lim, 2006).

Based on the method proposed by Kearsley and Mostert (2005b) for designing foamed concrete, a target casting density, s/c, and ash-cement ratios are chosen and the water requirement is determined. Using these values and the relative densities of the constituent materials, the mass of the cement and the volume of foam that should be added to obtain the required density can be determined. They have also proposed some equations for calculating the mixture proportions. Their method was based on establishing two variables, the cement content and the foam content, and then solving the two following equations:

$$p_m = x + x(w/c) + x(a/c) + x(s/c) + x(a/c)(w/a) + x(s/c)(w/s) + RD_f V_f$$

$$1000 = \frac{x}{RD_c} + x(w/c) + \frac{x(a/c)}{RD_a} + \frac{x(s/c)}{RD_s} + x(a/c)(w/a) + x(s/c)(w/s) + V_f$$

Where p_m is the target casting density (kg/m3), x is the cement content (kg/m3), w/c is the water/cement ratio, a/c is the ash/cement ratio, s/c is the sand/cement ratio, w/a is the water/ash ratio, w/s is the water/sand ratio, V_f is the volume of foam (L), RD_f is the relative density of foam, RD_c is the relative density of cement, RD_a is the relative density of ash, and RDs is the relative density of sand. The results were within 5% of the target density and show the suitability of this method.

V. PRODUCTION OF FOAMED CONCRETE

As mentioned earlier, the entrained air-void network can be produced in multiple ways. One such is through hydrogen gas, generated as a result of chemical reactions of aluminium powder in a slurry-made alkaline by the inclusion of Portland cement and sometimes also lime. These reactions are such that the aluminium powder, reacting with calcium hydroxide and water, releases hydrogen. The hydrogen gas in turn foams the raw mixture to double the volume (with gas bubbles up to 1/8 in. in diameter). At the end of the foaming process, the hydrogen escapes to the atmosphere and is replaced by air. In this method, after casting and the initial set, the material is then cured under steam (180 ̊ C – 210 ̊ C) at a very high pressure, that is, "autoclaved," for a specific amount of time to produce the final micro/macrostructure. This method was the earliest modern means of producing foamed concrete and was introduced in Scandinavia, notably Sweden and Denmark, in the 1920s.

Nowadays, foamed concrete is produced by the addition of foaming agents to the concrete mixture. This method has been in usage since the 1980s. The two basic methods of producing foamed concrete by using foaming agents are the prefoam and the mixing-foam methods.

In the prefoam method, the foaming agent is mixed with a part of the batch water in a foam generator and aerated to form the foam and then is forced at a high pressure through the foaming lance before being added to the mixture. The prefoamed method comprises aqueous surfactant solution and compressed air (Jones & McCarthy, 2005b).

In the mixing-foam method, the foaming agent is mixed with the matrix as a part of the constituent materials, that is, cement, water, and fine aggregates, if any. In general, the production of foamed concrete via the prefoam method can be divided into three stages: (1) preparing the paste or mortar, (2) preparing the foam from a pre-mixed foaming agent, and (3) generation of the foam using compressed air (Hamidah et al., 2005). For convenience and accuracy, the foam generator should be calibrated prior to mixing so that the calculated quantity of foam required for a mix can be converted to the more easily understood duration of foam generation.

For a given air content or volume of air, if the bubbles are too large, there will not be enough of them present to properly protect the paste. Large bubbles are also less stable and hence more likely to break while the concrete is being mixed, transported, placed, and, if necessary, vibrated. If too much air is lost during these operations, the remaining air voids may lead to a performance below that expected from the resultant foamed concrete (Timbrell, 2007).

VI. PROPERTIES OF FOAMED CONCRETE

As with any cement-based product, the characteristics of foamed concrete depend strongly upon its mixture composition. Nevertheless, some general properties may be identified (Aldrige, 2005): (1) high strength-to-weight ratio, (2) low coefficient of permeability, (3) low water absorption, (4) good freeze-thaw resistance, (5) rigid well-bonded microstructure, (6) low shrinkage, (7) thermally insulating, (8) shock absorption capacity, and (9) non-susceptibility to breakdown of hydrocarbons, bacteria, or UV radiation. The behaviour observed for normal concrete does not necessarily hold true for foamed concrete and for most properties; it would be unwise to assume, without experimental proof, behavioural trends for foamed concrete as mere lightweight extensions of our knowledge of conventional concrete.

A. Properties Of Fresh Foamed Concrete

1) *Workability and Water Demand:* In its fresh state, foamed concrete is a free flowing, self-compacting, and self leveling material and therefore is expected to yield a collapse slump, but it is known to exhibit a thixotropic behaviour (British Cement Association, 1994). It is easy to pump and flow into the most restricted and irregular of cavities (British Cement Association, 1994; Jones & McCarthy, 2005b). In its visual appearance, fresh foam concrete looks like a thin gray mousse or grayish milkshake. The effect of mixing time is very important. Usually, the more the mixing time, the more the entrained air. However, where the maximum air content (a critical limit) has been reached, further mixing may cause the loss of entrained air. In other words, increasing the time of mixing will produce higher air content but when a critical air content is exceeded, any further mixing causes a drop in the air content. This behaviour depends upon the amount, type, and efficiency of the foam or the air entraining agent (Beningfield et al., 2005). Note that the slump test is not an appropriate workability measure for foamed concrete, as the slump values lie in excess of about 200 mm. Instead, the water demand of the constituent materials used in

foamed concrete may be successfully determined using a flow table test (Beningfield et al., 2005; Kearsley & Mostert, 2005b). In the United Kingdom, the workability is evaluated by using the dropping ball consistency test as per BS 4551 (Beningfield et al., 2005). The w/c ratio is typically in the range of 0.4-0.8 depending on the mixture composition, consistency requirements, the use of chemical admixtures, and the foam stability (Jones & McCarthy, 2005b; Kearsley & Booysens, 1998). The w/c ratio should not be less than 0.35 before the introduction of the foam. Too little and the cementitious powder is prone to draw its moisture requirement from the foam, causing the latter to collapse partly or in full (Wee et al., 2006). Too much and the strength of the hardened concrete is compromised. In general, greater foamed concrete spreads are obtained with higher w/c ratios, and the consistency on average is reduced by a drop in the concrete plastic density, perhaps due to the lower self-weight (Jones & McCarthy, 2005b). Due to the presence of bubbles and the absence of coarse aggregate, foamed concrete, in general, has a higher consistency with no segregation or bleeding (Timbrell, 2007). However, some foam instability and mixture segregation have been observed when using GGBFS as a mineral admixture in foamed concrete (Jones & McCarthy, 2005b). Batool and Bindiganavile (2017) found that unlike FA or SF, MK increases the water demand in the foamed concrete system, for a given flow time. Kearsley and Mostert (2005b) found that if small volumes of sand (less than 25%) are added to the ash, no additional water is required to adjust the water content, and it remains suitable for use in foamed concrete. On the other hand, in mixtures that contain sand in excess of 25% (by volume), the water requirement was seen to increase dramatically. The replacement of sand with coarse FA is seen to significantly reduce the yield values in shear flow, and any increase in the plastic density leads to a corresponding drop in the plastic viscosity (Jones & McCarthy, 2005b). The flow behaviour of foamed concrete depends mainly on the foam volume, and it is reported that an increase in the foam volume results in a drop in the flow (Jones & McCarthy, 2006; Nambiar & Ramamurthy, 2006) (Figs.1 and 2). Moreover, the effect of cement content on the amount of air entrained in mixes that already contain an air entraining agent was substantial and studies show that an increase in the cement content leads to a drop in the air content (Beningfield et al., 2005).

2) *Density:* While it is used mostly in non-structural applications, foamed concrete must be designed for properties that are dependent on its density. However, while the mixture is cast to a target density, often there is some difference between the density when cast and the density of the hardened material. In addition, some properties are cited in the literature against the oven-dry density. The dry density of foamed concrete can be as low as 48 kg/m^3 to as high as 1800 kg/m^3 (Jones & McCarthy, 2005b; Kearsley & Wainwright, 2001b; Timbrell, 2007). Kearsley and Mostert (2005b) found a linear relationship between fresh density and the dry density of foamed concrete for different mix designs including different ash contents. They proposed the following linear equation for calculating the required casting density (ρ_{cast}) for concrete dry densities (ρ_{dry}) between 600 and 1200 kg/m^3:

$$\rho_{\text{cast}} = 1.034\rho_{\text{dry}} + 101.96$$

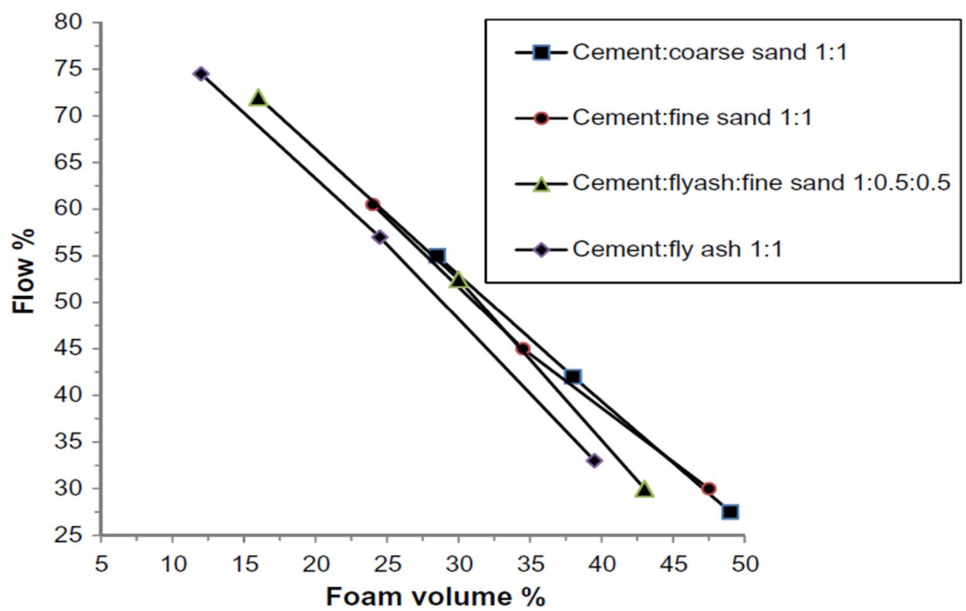


Figure 1 Effect of foam content on the flow in foam concrete (Jones & McCarthy, 2006).

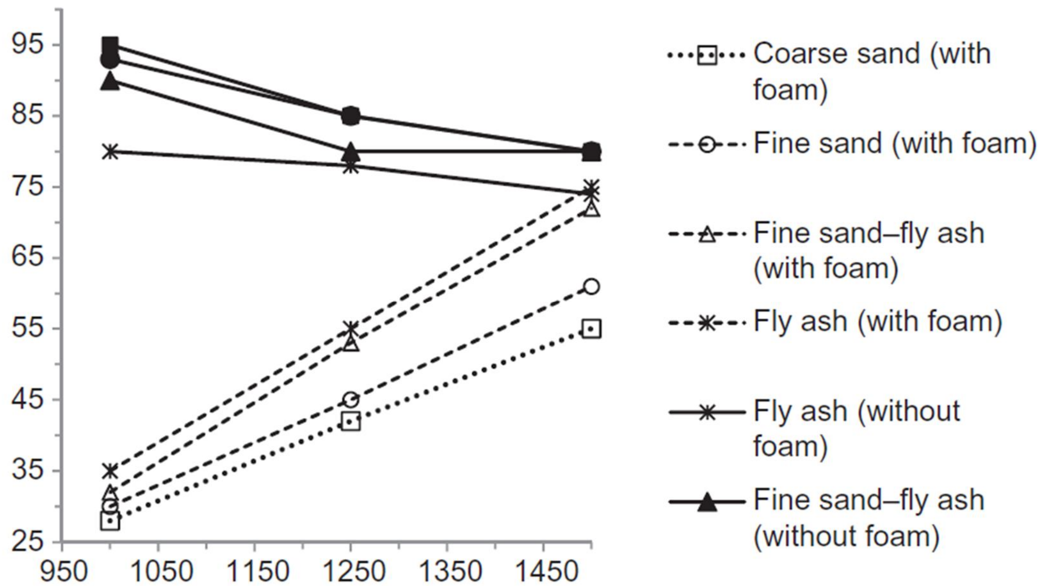


Figure 2 Variation of flow % with and without foam (Nambiar & Ramamurthy, 2006).

3) *Curing:* As the concrete hardens, the bubbles disintegrate or transform and, in the process, release their water to be absorbed into the cement matrix. Not only does this aid in the hydration process, it also creates air voids out of the network of pores previously filled with water. Thus, there is less need to keep the concrete damp during curing as is normally necessary with conventional concrete (Timbrell, 2007). Higher strengths have been obtained with air-curing in comparison to sealed or water-cured samples (Jones & McCarthy, 2005b). On the other hand, for mixes containing FA, the long-term strength gain is seen to be higher for well-cured samples (Kearsley & Wainwright, 2001b). Kearsley and Mostert (2005a) investigated the effect of different curing regimes on the properties of foamed concrete with FA. Based on their results a high temperature curing regime can significantly increase the rate of strength gain of mixtures containing a high volume of FA, but it results in a lower ultimate strength. However, the curing period required was significantly lower (less than 3 days) due to the high ambient temperature.

B. Properties Of Hardened Foamed Concrete

1) *Compressive strength:* The compressive strength of foamed concrete is mainly influenced by its density, and it decreases exponentially with a decrease in the foamed concrete density. For the typical range of densities in practice, the compressive strength may be as low as 0.34 MPa and as high as over 20 MPa (Aldrige, 2005; Hamidah et al., 2005; Jones & McCarthy, 2005b, 2006; Kearsley & Booysens, 1998; Kearsley & Mostert, 2005b). In the production of foamed concrete, it is usually desirable to obtain the highest possible strength at the lowest possible density. Ultimate strengths of more than 50 MPa have also been achieved by the application of FA in higher densities (1500 kg/m3) (Kearsley & Wainwright, 2001b). SF has also been added in foamed concrete at up to 10% by mass of cement and was found to be effective in improving the compressive strength without affecting the stability of the air-void system (Jones & McCarthy, 2005b). Kearsley and Wainwright (2002b) concluded that as with normal concrete, there is a correlation between the porosity and the compressive strength of foamed concrete and a decrease in the concrete porosity results in an increase in its strength. They proposed a relationship between the concrete strength and its porosity at a given w/c ratio (as described in Section 16.6.2.2). Higher compressive strength may be obtained by reducing the volume of voids required to obtain a given foamed concrete density. This is done by choosing constituent materials of low density for manufacturing the foamed concrete (Kearsley & Mostert, 2005a). Since the compressive strength of foamed concrete is mainly a function of its density, the Portland cement, supplementary cementing materials, and the filler, if any, may have a significant effect on the compressive strength (Kearsley & Mostert, 2005b; Kearsley & Wainwright, 2001b). Papayianni and Milud (2005) showed that high calcium FA increased the compressive strength of foamed concrete. They studied the compressive strength of foamed concrete with high calcium FA replacement up to 70%. The results indicate that by increasing the FA replacement up to 60%, compressive strength is seen to increase compared to the reference foamed concrete with no FA replacement. This increase continued even at 90 days of maturity. They concluded that

the higher water retention in FA (two times higher than that of cement) in combination with its pozzolanic reactivity seems to contribute to the superior performance of FA as a binder in cellular concrete. Moreover, based on the work by Kearsley and Wainwright (2002a), when using a coarser FA, high ash content results in a decrease in the early strength while the long-term strength is seen to improve. The study reports an optimum ash content for maximum strength after 1 year at nearly 60% of the cementitious materials content (Kearsley & Wainwright, 2002a). When cementitious fillers are used in foamed concrete, it is reported that the compressive strength continues to increase in the long term (Jones & McCarthy, 2005a). Using some other fine aggregates such as lime and recycled glass is seen to have little or no effect on the compressive strength (Jones & McCarthy, 2005b). Water-reducing chemical admixtures tend to cause instability in the foam and consequently are not normally used. In addition, in foamed concrete, small changes in the w/c ratio do not influence the strength in the way expected for normal weight concrete. Foamed concrete is characterized by its plastic density (Jones & McCarthy, 2006). In other words, the volume of the voids is an important determinant of strength as well as its w/c ratio and it is often the defining parameter. This is particularly true in the case of the more highly air entrained mixes (Wee et al., 2006). Moreover, it has been observed that increasing the water content results in an increase in the strength and the effect of void content seems to counteract the effect of the w/c ratio on the strength of foamed concrete. This is because foamed concrete is usually designed based on a desired density; the low density of water reduces the need to add foam to reach a target density (Kearsley & Mostert, 2005b). Thus, the long-held thumb rule of concrete technology, namely, that the strength is inversely proportional to the w/c ratio, is somewhat turned on its head in the case of foamed concrete. According to Nehdi and Khan (2003), the compressive strength of foamed concrete does not depend upon the w/c ratio, rather it is mostly affected by the foam content. The compressive strength of lower density foamed concrete can be increased to equal that of higher density foamed concrete by increasing the cement content (Hamidah et al., 2005). On the other hand, it is reported that in heavier foamed concrete that accommodates fine aggregate, higher s/c ratios result in lower compressive strength (Hamidah et al., 2005; Wee et al., 2006). As mentioned before, the compressive strength of foamed concrete is influenced by the type of foaming agent used. It is observed that protein-based foams increase the compressive strength of foamed concrete more than synthetic foams (Jones & McCarthy, 2005b), primarily through the creation of a closed cell network. It should be noted that in comparing the properties of foamed concrete, the type of foaming agent is important and only those mixes with the same type of foaming agents should be compared.

2) *Thermal properties:* Foamed concrete has a low thermal conductivity, which makes it a good insulating material. This is mainly because of its cellular structure. The thermal resistance (as a measure of insulation) ranges from R=2 to R=4. In comparison, regular concrete typically has a thermal resistance below R=1. The values for thermal conductivity of foamed concrete are typically 5%-30% of those measured for normal concrete and range between 0.1 and 0.7 W/m K for dry densities between 600 and 1600 kg/m3 and 0.23 and 0.42 W/m K for dry density of 1000-1200 kg/m3. Still it further reduces with a decrease in the dry density for lightweight foams (Jones & McCarthy, 2005b, 2006). ACI 523.2R-96 (1996) introduced the following design values for low-density concretes (densities between 320 and 800 kg/m3), namely, 0.09-0.2 W/m K for oven dry densities and 0.12-0.26 W/m K for air dry densities, respectively. A note of caution: if foamed concrete is used in elements with high volume-to-surface ratio, the low thermal conductivity of this material can lead to core temperature rise due to the heat of hydration and may cause cracking. When examining the effect of mineral admixtures, Batool and Bindiganavile (2017) found SF to be superior to FA and MK in reducing the thermal conductivity at a given dosage. This was attributed in part to the higher pozzolanic activity in the former and to the higher water retention associated with introducing MK.
3) *Porosity:* The pore structure of foamed concrete consists of gel pores, capillary pores, and air voids (air-entrained and air-entrapped pores). As foamed concrete is self-compacting and self-flowing, the possibility of entrapped air is negligible. Wee et al. (2006), Kearsley and Wainwright (2002b), and Hoff (1972) developed strengthporosity models for foamed concrete that show the effect of porosity of foamed concrete on its compressive strength. Their models show that decreasing the concrete porosity results in increasing the strength. Kearsley and Wainwright (2002b) found that the best equation that fits their result can be expressed as follows:

$$f_c = 981\mathrm{e}^{-7.43p}$$

where fc is the compressive strength of foamed concrete, and p is the porosity. Similarly, Wee et al. (2006) have proposed a relationship between the concrete strength and its porosity at a given w/c ratio as

$$\sigma = 1.262\sigma p(1-A)^{2.962}$$

where σ, σ_p, and A are the compressive strength of foamed concrete, compressive strength of the cement paste, and the air content, respectively.

Nambiar and Ramamurthy measured the air-void network of foam concrete, and it is reported that the volume, size, and spacing of the voids together influence the density and the mechanical properties of cement-based foams, but on the other hand, the shape of the air void does not influence the strength (Jones & McCarthy, 2006; Wee et al., 2006). Moreover, concrete with a higher air content tends to contain larger air voids, especially at air contents over 40% (Babu, Wee, & Tamilselvan, 2005). The fine fractions influence the air voids, and the use of FA is seen to result in a more uniform distribution of air voids and is recommended over using fine sands (Nambiar & Ramamurthy, 2007). While a narrow range of cell size favours lower thermal conductivity, Batool and Bindiganavile (2018) found that there was a drop in thermal conductivity with an increase in the mean cell size.

4) *Fire Resistance:* In regular concrete, the loss of strength due to high temperature is influenced primarily by the cement type and the aggregate type used. Foamed concrete is non-combustible and its fire resistance is very good and shows better performance than normal weight concrete at lower temperatures. This response improves with lower densities. Kearsley and Mostert (2005c) investigated the fire resistance of foamed concrete with high alumina cement and one type of an unclassified FA. They observed that the type of FA, aggregate type and cement type, can influence the fire resistance of foamed concrete. While foamed concrete containing Portland cement can withstand temperatures as high as 800℃, the mixtures containing hydraulic cement with an Al2O3/CaO ratio higher than 2 and andalusite aggregates, can withstand temperatures as high as 1450℃ without showing any signs of damage. Moreover, foamed concretes based on alkaline Portland cements and at a density of 500 kg/m^3 have been shown to be effective as fire resistance materials with a residual compressive strength after firing up to five times of strength before firing (Krivenko et al., 2005). However, at higher temperatures, cement-based foams undergo excessive shrinkage and research is ongoing in this area (Jones & McCarthy, 2005b).
5) *Shrinkage:* Because foamed concrete has relatively high paste content and no coarse aggregate, it will shrink more than normal concrete. It is interesting that no plastic shrinkage is reported in foamed concrete but drying shrinkage of this type of concrete is high, with values normally between 0.1% and 0.35% and lower density mixes have greater shrinkage strains (British Cement Association, 1994; Jones & McCarthy, 2005b). Papayianni and Milud (2005) studied the drying shrinkage of foamed concrete with high calcium FA replacement up to 70% and found that replacement of cement by this type of FA decreases the drying shrinkage from about 1800 μ-strains for reference concrete (without FA) to about 1200 μ-strains for foamed concert containing 60% FA. They also observed that the higher the strength, the lower the shrinkage. Similar investigation in reducing drying shrinkage of foamed concrete by using unclassified FA has been reported by Kearsley (1999). While ACI 523 2R-96 (1996) limits the average drying shrinkage of cellular concretes to 0.2%, the drying shrinkage for some typical foamed concrete with a s/c ratio of 2 and water to binder of 0.65 and 0.7 with a dry density of 1500-1600 kg/m3 have been reported as being much lower (less than 0.09%) (Lee & Hung, 2005).
6) *Water absorption:* The water absorption of foamed concrete depends on its density (which itself is a function of the foam content and the mix design). When represented as a percentage of original mass, the absorption of water increases with a decrease in the density and can be as low as 15% for a density of 1800 kg/m3 and as high as 35% for a density of 700 kg/m3 (Nambiar & Ramamurthy, 2006; Wee et al., 2006). The presence of fine aggregates has a bearing on the absorption for identical w/c ratios. Water absorption tests on foam concrete resulted in higher values for mixtures that contained FA instead of fine sand (Jones & McCarthy, 2005a, 2005b). Nambiar and Ramamurthy (2006) proposed that water absorption of foamed concrete should be represented in kg/m3 of foamed concrete rather than as a percentage of weight and by this expression; it increases with a reduction in the density. Since water absorption is mainly influenced by the paste, this trend is because of the relatively lower paste volume for lower densities, which results in smaller capillary pore volume. Similar results were obtained by Bagheri, Parhizkar, and Ghasemi (1999). They showed that the increase in the absorption for lower densities is due to the lower weight of the material itself. Further, they concluded that stating the absorption on the basis of volume will yield almost similar results in equal w/c ratios regardless of the density of the foamed concrete.
7) *Permeability:* All permeability indices of foamed concrete (air permeability, oxygen permeability, and water permeability) are known to increase with a drop in the density. This increase in permeability is also faster than that seen for regular concrete (Jones & McCarthy, 2005b; Kearsley & Booysens, 1998; Kearsley & Mostert, 2005b; Kearsley & Wainwright, 2001a; Lee & Hung, 2005). However, Kearsley and Booysens (1998) and Kearsley (1999) have reported that the oxygen permeability of foamed concrete with a density of 1500 kg/m^3 was less than that of a normal weight concrete with a compressive strength of 25 MPa and so, at high densities, foamed concrete could be at least as durable as normal concrete of equal density. The average coefficient of water permeability of some typical foamed concrete samples as measured in accordance with ISO/DIS 7031 (1983) was in the order of 10210 m/s, where the dry density was in the range of 1500-1600 kg/m3 (Lee & Hung, 2005).

VII. APPLICATIONS

Applications for foamed concrete include cavity filling and insulation for lower densities on the one hand and structural applications for higher densities on the other.

The properties associated with very low density, including a low thermal conductivity, superior flowability, self-compacting nature, and its ease of manufacture and relatively low cost, make foamed concrete applications in a wide range of areas.

Interest in cellular "foamed concrete" has been widespread in all parts of Canada, the United States, and Mexico, as well as in the other parts of the world, especially regions with housing shortages, recent adverse weather, hurricanes, earthquakes, etc. The overall interest and demand appears to be equal to the actual production, with demand being more from the southern United States and regions with longer construction seasons. Particularly in Canada, cellular grouts have been used for tunnel annulus grouting, flowable fills, and other geotechnical applications over the years, but a keen interest and a tremendous expansion of application and use has developed over about the past 10-15 years. This increased interest appears to be due in part to dramatic increases at the costs of construction materials, especially wood, dry wall, cement, etc. and in part to the associated environmental issues, fuel costs, and energy consciousness. An additional major factor has been the shortage and huge cost increases of cement.

Over the past decade, interest and actual development of cellular products has dramatically increased to include the development of new building materials (i.e., cellular wall panels, blocks, architectural items, void fills). Building product applications of cellular concrete have been used in Europe for over 50 years but have caught on in the United States and Canada more recently.

Foamed concrete is used in order to prevent frost heave in roads, under concrete paving, to insulate shallow foundation systems, to prevent frost jacking of shallow piles, to prevent frost heave under pile caps, to act as backfill under buried oil field modules, for tank support, and to reduce the temperature under hot oil tanks. It is also useful to reduce the thermal gradient and thermal stress in hot concrete pits and thus insulate shallow placed utilities. As a filler, it is used as a grout to fill abandoned pipes and fill voids under slabs.

The market in Western Canada is approximately 50,000 m^3/year. The annual market size for foamed concrete in the United Kingdom is estimated around 250,000-300,000 m^3 (this excludes one unique and very large mine stabilization project) (Beningfield et al., 2005; Jones & McCarthy, 2005b). In the Middle East, foamed concrete is used both as a good thermal insulator for its lightweight. It is hence used to reduce the effect of earthquakes.

In Holland, very high air-entrained concrete forms the road subbase where the load carrying capacity is low. Because of its low density, when used in the construction of bridge abutments, it does not impose large lateral loads. Thus huge cost savings can be achieved by reducing the thickness of the walls and the size of the foundations.

As it is capable of flowing under its own weight, it is an ideal material for voids (old sewers, basements, ducts, storage tanks and voids under roadways caused by heavy rain). Other applications of foamed concrete include trench reinstatement, acoustic insulation, production of light weight blocks and precast panels, and soil stabilization.

Engineers continue to use and find other applications for cellular concrete. It can be easily excavated if necessary and hence more labour friendly at times of repair and rehabilitation.

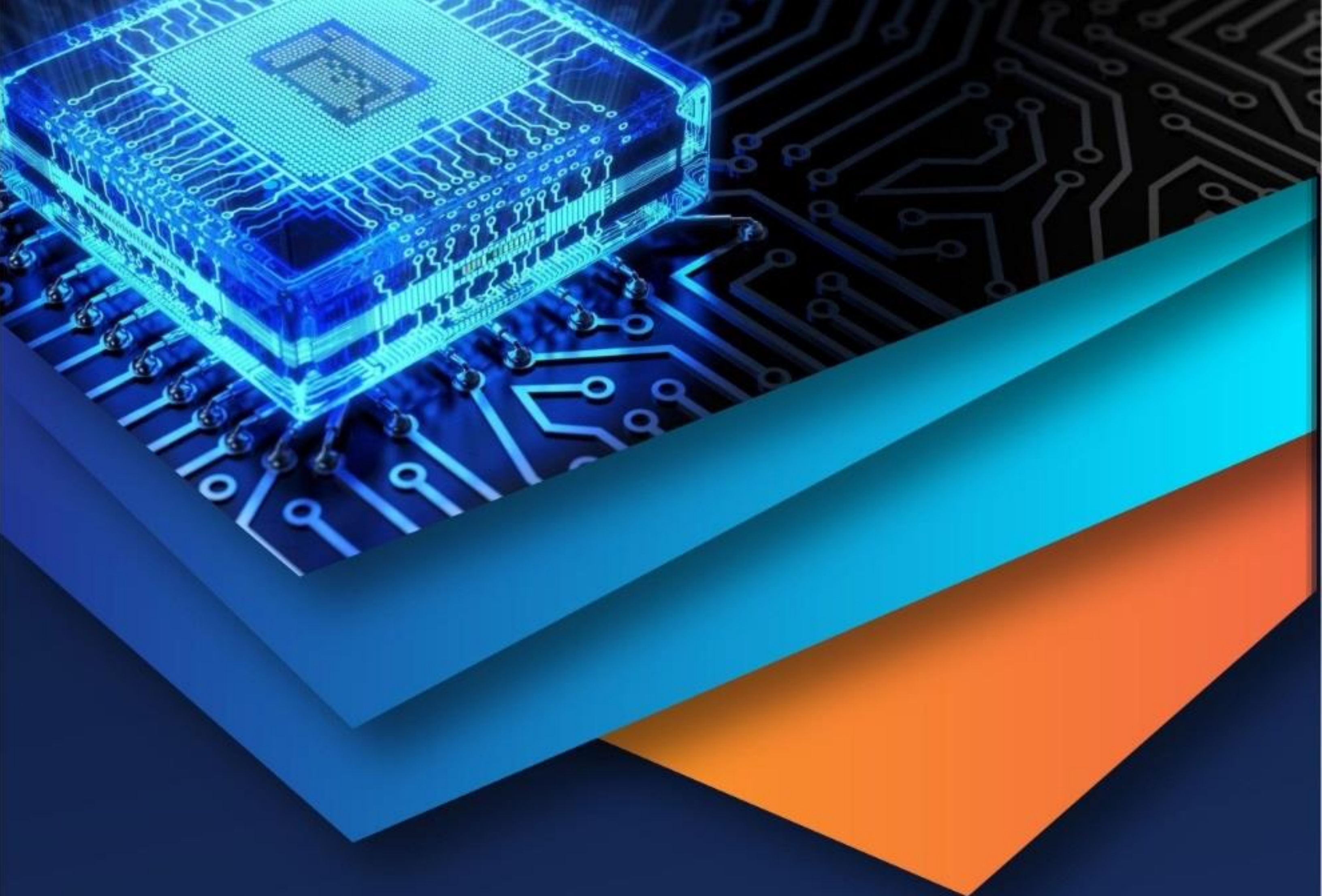
VIII. RESEARCH NEEDS

Although it has been extensively investigated during the 1960s and 1970s (Hoff, 2003), several factors necessitate a fresh look at the science and technology of cement-based foams. These include (1) the development of advanced foaming agents, foam stabilizers, chemical and mineral admixtures, and reinforcement; (2) a growing environmental awareness regarding cement-based products; (3) applications that involve extreme loading, temperatures, and acoustics; (4) the ongoing quest for building materials with superior performance-to-weight characteristics. Therefore, notwithstanding the attributes listed in the preceding discussion, foamed concrete has a significant potential for additional utilization, which can be achieved through further research in a number of areas. There is an ongoing need for innovative chemical admixtures that do not affect the foam stability or segregation in the mix. For instance, superplasticizers that maintain the air-void network will facilitate the addition of fibers and lightweight fillers to improve both the strength and the fracture toughness without raising the overall density. In addition, other chemical admixtures such as accelerators and retarders must be made compatible with the foaming agents to allow for larger volume of pours, with a reduced heat of hydration. There is a need to study the engineering properties of foamed concrete in greater detail. In particular, the modulus of elasticity, Poisson's ratio, and creep must be characterized in order to aid in the structural design. Besides, the coefficient of thermal expansion and specific heat must be charted for a range of densities and compositions. Although it has excellent fire resistance, foamed concrete undergoes excessive shrinkage at very high temperatures, and the reasons are unclear (Sach & Seifert, 1999). Research is needed to understand the mechanisms underlying this behaviour.

REFERENCES

[1] Abdollahnejad, Z., Pacheco-Torgal, F., Flix, T., Tahri, W., & Barroso Aguiar, J. (2015). Mix design, properties and cost analysis of fly ash-based geopolymer foam. Construction and Building Materials, 80, 18-30.
[2] ACI 523.1R-06. (2006). Guide for cast-in-place low density cellular concrete. ACI Committee 523.
[3] ACI 523.2R-96. (1996). Guide for precast cellular concrete floor, roof, and wall units. ACI Committee 523.
[4] Aldrige, D. (2005). Introduction to foamed concrete. Proceeding of the international conference on use of foamed concrete in construction. Scotland: University of Dundee.
[5] Arellano Aguilar, R., Burciaga Dı´az, O., & Escalante Garcı´a, J. I. (2010). Lightweight concretes of activated metakaolin-fly ash binders, with blast furnace slag aggregates. Construction and Building Materials, 24, 1166-1175.
[6] ASTM C618-05. (2005). Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. ASTM International.
[7] ASTM C666-97. (2015). Standard test method for resistance of concrete to rapid freezing and thawing. ASTM International.
[8] ASTM C796-04. (2004). Standard test method for foaming agents for use in producing cellular concrete using preformed foam. ASTM International.
[9] ASTM C869-91. (2006). Standard specification for foaming agents used in making preformed foam for cellular concrete. ASTM International.
[10] Babu, D.S., Wee, T.H., & Tamilselvan, T. (2005). Mechanical properties of foamed concrete with and without aggregates. In Proceedings: ConMat '05 and Mindess symposium. Vancouver.
[11] Bagheri, T., Parhizkar, A.M., & Ghasemi, R. (June 1999). Foam concrete: Properties and application areas. In Proceeding of annual conference of Canadian Society of Civil Engineering (pp. 101-110). Regina, Canada.
[12] Batool, F., & Bindiganavile, V. (2017). Effect of pozzolanic admixtures on thermal properties of lightweight cement-based foams. Journal of Testing and Evaluation, 45(5), 1764-1776.
[13] Batool, F., & Bindiganavile, V. (2018). Quantification of factors influencing the thermal conductivity of cement-based foam. Cement and Concrete Composites, 91, 76-86.
[14] Beningfield, N., Gaimster, R., & Griffin, P. (July 2005). Investigation into the air void characteristics of foamed concrete. Proceedings: International conference on the use of foamed concrete in construction (pp. 51-60). Scotland: University of Dundee.
[15] British Cement Association. (1994). Foamed concrete: Compositions and properties. Camberley, UK.
[16] Cox, L. S. (July 2005). Major road and bridge projects with foam concrete. Proceedings: International conference on use of foamed concrete in construction (pp. 105-112). Scotland: University of Dundee.
[17] Cox, L. S., & van Dijk, S. (2002). Foam concrete: A different kind of mix. Concrete (UK), 36(2), 54-55.
[18] Goual, M. S., Bali, A., de Barquin, F., Dheilly, R. M., & Queneudec, M. (2006). Isothermal Moisture properties of clayey cellular concretes elaborated from clayey waste, cement and aluminium powder. Cement and Concrete Research, 36, 1768-1776.
[19] Hamidah, M. S., Azmi, I., Ruslan, M. R. A., Kartini, K., & Fadhil, N. M. (2005). Optimization of foamed concrete mix of different sand/cement ratio and curing conditions. Proceedings: International conference on the use of foamed concrete in construction (pp. 37-44). Scotland: University of Dundee.
[20] Hoff, G. C. (1972). Porosity-strength considerations for cellular concrete. Cement and Concrete Research, 2(1972), 91-100.
[21] Hoff, G. C. (2003). Discussion of 'Development of Deformable Protective System for Underground Infrastructure using Cellar Grouts'. ACI Materials Journals, 100(4), 350-351.
[22] Ibrahim, W. M. W., Hussin, K., Bakri Abdullah, M., Mustafa, A. L., & Kadir, A. A. (2017). Geopolymer lightweight bricks manufactured from fly ash and foaming agent. AIP Conference Proceedings, 1835(1), 1-5.
[23] ISO/DIS 7031. (1983). Concrete hardened—Determination of the depth of penetration of water under pressure. ISO.
[24] Jones, M. R., & McCarthy, A. (2006). Heat of hydration in foamed concrete: Effect of mix constituents and plastic density. Cement and Concrete Research, 36(2006), 1032-1041.
[25] Jones, M. R., & Giannakou, A. (2004). Thermally insulating foundations and ground slabs using highly-foamed concrete. Journal of ASTM International, 1(6), 100-112.
[26] Jones, M. R., & McCarthy, A. (2005a). Preliminary views on the potential of foamed concrete as a structural material. Magazine of Concrete Research, 57(1), 21-31.
[27] Jones, M. R., & McCarthy, A. (2005b). Behaviour and assessment of foamed concrete for construction application. Proceedings: International conference on the use of foamed concrete in construction (pp. 61-88). UK: Univ. of Dundee.
[28] Jones, M. R., & McCarthy, A. (2006). Utilization of unprocessed low-lime fly ash in foamed concrete. Fuel, 84(11), 1398-1409.
[29] Kearsley, E.P. (1996). The use of foamcrete for affordable development in third countries. In Appropriate concrete technology, proceedings from the international conference on 'concrete in the service of mankind' (pp. 233-243). London.
[30] Kearsley, E. P. (1999). Just foamed concrete: An overview. Specialist techniques and materials for concrete construction, proceeding of the international conference (pp. 227-237). Scotland: University of Dundee.
[31] Kearsley, E. P., & Booysens, P. J. (1998). Reinforced foamed concrete, can it be durable? Concrete Beton (91), 5-9.
[32] Kearsley, E. P., & Mostert, H. F. (2005a). Opportunities for expanding the use of foamed concrete in the construction industry. Proceedings: International conference on use of foamed concrete in construction (pp. 143-154). Scotland: University of Dundee.
[33] Kearsley, E. P., & Mostert, H. F. (2005b). Designing mix composition of foamed concrete with fly ash contents. Proceedings: International conference on use of foamed concrete in construction (pp. 29-36). Scotland: University of Dundee.
[34] Kearsley, E. P., & Mostert, H. F. (2005c). The use of foamed concrete in refractories. Proceedings: International conference on use of foamed concrete in construction (pp. 89-96). Scotland: University of Dundee.
[35] Kearsley, E. P., & Wainwright, P. J. (2001a). Porosity and permeability of foamed concrete. Cement and Concrete Research, 31(2001), 805-812.
[36] Kearsley, E. P., & Wainwright, P. J. (2001b). The effect of high fly ash content on the compressive strength of foamed concrete. Cement and Concrete Research, 31(2001), 105-112.
[37] Kearsley, E. P., & Wainwright, P. J. (2002a). Ash content for optimum strength of foamed concrete. Cement and Concrete Research, 32(2002), 241-246.
[38] Kearsley, E. P., & Wainwright, P. J. (2002b). The effect of porosity on the strength of foamed concrete. Cement and Concrete Research, 32(2002), 233-239.

[39] Krivenko, P. V., Kovalchuk, G. Y., & Kovalchuk, O. Y. (2005). Heat resistant cellular concrete based on alkaline cements. Proceedings: International conference on use of foamed concrete in construction (pp. 97-104). Scotland: University of Dundee.
[40] Lee, H. K., & Liang, Z. (2004). Computational modeling of the response and damage behaviour of fiber reinforced cellular concrete. Computers and Structures, 82(2004), 581-592.
[41] Lee, Y. L., & Hung, Y. T. (2005). Exploitation of solid wastes in foamed concrete: Challenges ahead. Proceedings: International conference on use of foamed concrete in construction (pp. 15-22). Scotland: University of Dundee.
[42] Liu, Z., Kong, F.-L., Shao, N.-N., Zhang, J.-J., Chen, Z.-Z., & Wang, D.-M. (2016). Strength and Microstructure of alkali-activated fly ash-slag foam geopolymer. Journal of Solid Waste Technology and Management, 42(1), 16-26.
[43] Mamun, M., Batool, F., & Bindiganavile, V. (2014). Thermo-mechanical properties of fibre reinforced cement-based foam exposed to sulphate. Construction and Building Materials, 61, 312-319.
[44] Mamun, M., & Bindiganavile, V. (2014). Specimen size effects and dynamic fracture toughness of cement based foams. ASCE Journal of Materials in Civil Engineering, 26(1), 143 151.
[45] Nambiar, E. K. K., & Ramamurthy, K. (2006). Influence of filler type on the properties of foam concrete. Cement & Concrete Composites, 28(2006), 475-480.
[46] Nambiar, E. K. K., & Ramamurthy, K. (2007). Air-void characterization of foam concrete. Cement and Concrete Research, 37(2007), 221-230.
[47] Nehdi, M., & Khan, A. (2003). Development of deformable protective system for underground infrastructure using cellular grouts. ACI Materials Journal, 99(5), 490-498.
[48] Novais, R. M., Ascensao, G., Labrincha, J. A., Buruberri, L. H., & Seabra, M. P. (2016). Porous biomass fly ash-based geopolymers with tailored thermal conductivity. Journal of Cleaner Production, 119, 99-107.
[49] Papayianni, I., & Milud, I. A. (July 2005). Production of foamed concrete with high calcium fly ash. Proceedings: International conference on use of foamed concrete in construction (pp. 23-28). Scotland: University of Dundee.
[50] Proshin, A. P., Beregovoi, V. A., Beregovoi, A. M., & Eremkin, A. I. (July 2005). Unautoclaved foam concrete and its construction adapted to regional conditions. Proceedings: International conference on the use of foamed concrete in construction (pp. 113-120). Scotland: University of Dundee.
[51] Provis, J. L., & Van Deventer, J. S. J. (2014). Alkali activated materials: State-of-the-art report, RILEM TC 224-AAM. Dordrecht: Springer.
[52] South African Bureau of Standards (SABS) 1491: Part II. (1989). Portland cement extenders Part II: Fly ash. South African Bureau of Standards.
[53] Sach, J., & Seifert, H. (1999). Foamed concrete technology: Possibilities for thermal insulation at high temperatures. CFI Forum of Technology, DKG, 76(9), 23-30.
[54] Singh, B., Ishwarya, G., Gupta, M., & Bhattacharyya, S. K. (2015). Geopolymer concrete: A review of some recent developments. Construction and Building Materials, 85, 78-90.
[55] Skvara, F., Jilek, T., & Kopecky, L. (2005). Geopolymer materials based on fly ash. Journal Ceramics-Silika´ty, 49(3), 195-204.
[56] Skvara, F., Sulc, R., Zdenek, T., Petr, S., Vit, S., & Zlamalova, C. Z. (2014). Preparation and properties of fly ash-based geopolymer foams. Ceramics-Silikaty, 58(3), 188-197.
[57] Stolz, J., Boluk, Y., & Bindiganavile, V. (2018). Mechanical, thermal and acoustic properties of cellular alkali activated fly ash concrete. Cement & Concrete Composites, Nov 2018, 94, 24-32.
[58] Tikalsky, P. J., Pospisil, J., & MacDonald, W. (2004). A method for assessment of the freeze thaw resistance of preformed foam cellular concrete. Cement and Concrete Research, 34(2004), 889-893.
[59] Wee, T.-H., Babu, D. S., Tamilselvan, T., & Lim, H.-S. (2006). Air-void system of foamed concrete and its effect on mechanical properties. ACI Material Journal, 103, 45-52.
[60] Weiss, C. A., Jr., Tom, J. G., & Malone, P. G. (August 2005). Foamed fiber-reinforced concrete as a construction material for live-fire training ranges. In Proceedings: ConMat ’05 and Mindess symposium. Vancouver.
[61] Zhang, Z., Provis, J. L., Reid, A., & Wang, H. (2015). Mechanical, thermal insulation, thermal resistance and acoustic absorption properties of geopolymer foam concrete. Cement and Concrete Composites, 62, 97-105.
[62] Zollo, R. F., & Hays, C. D. (1998). Engineering material properties of a fiber reinforced cellular concrete. ACI Materials Journal, 95(5), 631-635.



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