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Md Azree Othuman Mydin, Norizal Md Noordin

Mechanical, Thermal and Functional Properties of Green Lightweight Foamcrete

In recent times, the construction industry has revealed noteworthy attention in the use of lightweight foamcrete as a building material due to its many favourable characteristics such as lighter weight, easy to fabricate, durable and cost effective. Foamcrete is a material consisting of Portland cement paste or cement filler matrix (mortar) with a homogeneous pore structure created by introducing air in the form of small bubbles. With a proper control in dosage of foam and methods of production, a wide range of densities (400 – 1600 kg/m^3) of foamcrete can be produced thus providing flexibility for application such as structural elements, partition, insulating materials and filling grades. Foamcrete has so far been applied primarily as a filler material in civil engineering works. However, its good thermal and acoustic performance indicates its strong potential as a material in building construction. The focus of this paper is to classify literature on foamcrete in terms of its mechanical, thermal and functional properties.

Keywords: *foamed concrete, thermal properties, mechanical properties, functional properties, lightweight concrete*

1. Introduction

Foamcrete is defined as a cementitious material having a minimum of 20 per cent by volume of mechanically entrained foam in the mortar slurry [1] in which air-pores are entrapped in the matrix by means of a suitable foaming agent. The air-pores are initiated by agitating air with a foaming agent diluted with water; the foam then carefully mixes together with the cement slurry to form foamcrete. Integrating the air-pores into the base matrix gives a low self-weight, high workability, but lower strength in contrast to normal weight concrete. Foamcrete can be fabricated anywhere in any shape or building unit size. Table 1 shows the range of densities suitable for different applications.

2. Constituents Material Of Foamcrete

Foamcrete with low density, i.e. having a dry density of up to about 600 kg/m^3, is frequently formed from cement (to which other binders could be added), water and stable foam whilst denser foamcrete will incorporate fine sand in the mix. The requirements of each constituent of foamcrete are explained below.

2.1. Cement

Portland cement SEM1 is typically used as the main binder for foamcrete. Additionally, rapid hardening Portland cement [2], calcium sulfoaluminate and high alumina cement have also been used to reduce the setting time and to obtain better early strength of foamcrete.

There was also an attempt to decrease the cost of production by using fly ash [3] as cement replacement to enhance consistency of the mix and to reduce heat of hydration while contributing for long term strength.

2.2. Fillers (sand)

[4] suggested that only fine sands having particle sizes up to about 4mm and with an even distribution of sizes should be used for foamcrete. This is primarily because coarser aggregate might lead to collapse of the foam during the mixing process. Coarse pulverised fuel ash (PFA) also can be used as a partial or total replacement for sand to make foamcrete with a dry density below about 1400 kg/m^3.

2.3. Water

The amount of water to be added to the mix depends on the composition of the mix design. Generally for lighter densities, when the amount of foam is increased, the amount of water can be decreased. The water-cement ratio must be kept as low as possible in order to avoid unnecessary shrinkage in the moulds.

However, if the amount of water added to cement and sand is too low, the necessary moisture to make a workable mix will have to be extracted from the foam after it is added, thereby destroying some of the foam in the mix. The range of water-cement ratio used in foamcrete is between 0.4 to 1.25 [5], the appropriate value will be depending on the amount of cement in the mix, use of chemical admixtures and consistence requirement.

2.4. Surfactants (foaming agent)

There is an extensive choice of surfactants (foaming agent) available in the market. Generally two types of surfactants can be used to produce foam: protein and synthetic based surfactants. Protein based surfactants are produced from refined animal products such as hoof, horn and skin whilst synthetic based surfactants are produced using man made chemicals such as the ones used in shampoos, soap powders and soaps.

The surfactant solution typically consists of one part of surfactant and between 5 and 40 parts of water but the optimum value is a function of the type of surfactant and the technique of production. It is very important to store all surfactants accordingly because they are inclined to deterioration at low temperatures.

Foams formed from protein based surfactants have smaller bubble size, are more stable and have a stronger closed bubble structure compared to the foam produced using synthetic surfactants. Therefore, protein based surfactants would be best suited for the production of foamcrete of comparatively high density and high strength.

3. Design Procedure

At the moment, there is no standard method for designing foamcrete mix. For normal weight concrete, the user would signify a certain compressive strength and the water-cement ratio would be adjusted to meet the requirement. As far as foamcrete is concerned, not only the strength is specified, but also the density. It is not an easy task to achieve an accurate measurement of the density of foamcrete on site because of the hardened density of foamcrete depends on the saturation intensity in its pores. It is difficult to achieve the design density of foamcrete because it has a tendency to lose between 50 and 200 kg/m^3 of the total mix water because it depends on the concrete fresh density, early curing regime and exposure conditions.

4. Relevant Studies on Properties of Foamcrete

There is a lack of published information on foamcrete. Among the foamcrete related literature collected by the author, majority of these were published within the last 10 years and most of these previous studies on foamcrete were aimed at characterizing the ambient temperature properties of foamcrete. This section will review previous studies on properties of hardened foamcrete, including physical properties (density, air-void system and porosity), mechanical properties (compressive strength, tensile strength and modulus of elasticity), thermal properties and fire resistance performance.

4.1 Density of foamcrete

The relationship between dry density and casting density between 600 kg/m^3 and 1200 kg/m^3 can be calculated using the following linear equation (Kearsley and Mostert, 2005):

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

where ρ_m is the target casting density (kg/m^3) and ρ_{dry} is the dry density (kg/m^3)

4.2. Air-void system and porosity of foamcrete

Porosity and the pore structure will have significant effects on thermal conductivity and mechanical properties of foamcrete. High porosity is highly detrimental to the strength of foamcrete, particularly if the pores are of large diameter. Large pores also result in high thermal conductivity. As a cement-based material, foamcrete consists of gel-pores (dimensions from 0.0005μm up to 0.01μm), capillary-pores (0.01μm to 10μm) and air-pores (air entrained and entrapped pores) [6].

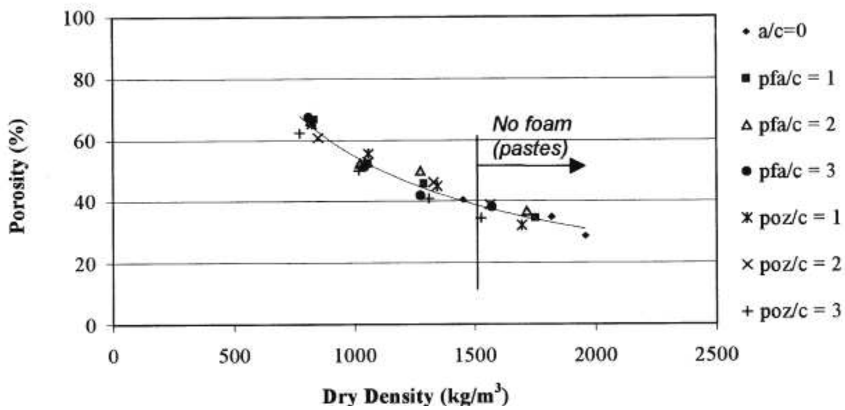

Figure 1. Porosity of foamcrete as a function of dry density [3]

The gel-pores occupy between 40 to 55% of total pore volume but they are not active in permeating water through cement paste and they do not influence the strength [7]. However, the water in the gel-pores is physically bonded to cement and directly controls shrinkage and creep properties of foamcrete.

Air-pores in hardened foamcrete can be entrained or entrapped. Entrapped air-pores occur inadvertently during the mixing and placing of concrete. As foamcrete is a self-flowing and self-compacting concrete and exclusive of any coarse aggregate, the possibility of entrapped air is insignificant. In contrast, entrained air-pores are introduced intentionally during production of foamcrete by using an air-entraining chemical admixture (surfactants). Entrained air-pores are discrete and individual bubbles of spherical shape. They are uniformly distributed throughout the cement paste and are not interconnected with each other and therefore do not affect the permeability of foamcrete. The total volume of capillary-pores and air-pores affects the strength of foamcrete.

Kearsley and Wainwright [8] carried out research to investigate the relationship between porosity and dry density of foamcrete. In this study, they utilized a large amount of both classified and unclassified fly ash (pulverised and pozz-fill) as a cement replacement up to 75% by weight. Figure 1 shows the relationship between porosity and dry density of foamcrete obtained from their research. It can be seen from Figure 1 that there is a strong relationship between porosity and dry density of foamcrete. They found that the porosity of foamcrete is the combination of entrained air-pores and the pores within the paste and the porosity was found to be dependant primarily on dry density of foamcrete and not on fly ash type and content. They proposed an equation to link the porosity and dry density of foamcrete (based on Figure 1) as follows:

$$\varepsilon = 18700\rho_{dry}^{-0.85} \quad \ldots \qquad \ldots(2)$$

where ε is the porosity (%) and ρ_{dry} is the dry density (kg/m^3)

4.3. Compressive strength of foamcrete

The compressive strength of foamcrete reduces with decreasing density. Table 1 shows a summary of the range of compressive strength of foamcrete for various mixture composition and densities reported in literature. For mixes with similar constituents, the density-strength relations should be reasonably comparable. But, because the constituents in foamcrete mixtures can differ widely, density is not necessarily a dependable indicator of the compressive strength of foamcrete. The other main factors that influence the strength of foamcrete are cement-sand ratio, water-cement ratio, type of cement and content, pore size and distribution, type of surfactants (foaming agents) and curing regime [9,10]. Higher sand-cement ratios result in foamcrete with lower compressive strength. The strength of lower density foamcrete can be increased to equal that of higher density foamcrete by increasing the amount of cement content in the mix.

The effect of water-cement ratio on compressive strength of foamcrete is imprecise. [11] reported that the strength of foamcrete decreases with reduction in water-cement ratio. Whilst an other report indicates that the compressive strength of foamcrete reduces with increasing water-cement ratio up to 0.45, an opposite trend is noted above this value (between 0.5 and 1.0) [11]

Table 1. Review of foamcrete mixes, strengths and density ranges [12]

Authors	Proportion of cement (kg/m^3) or composition	Ratios			Density range kg/m^3	Compressive strength (28 days) N/mm^2
		S/C	W/C	F/C		
Van Deijk (1991)	Cement-sand/ fly ash	-	-	-	280-1200	0.6 -10.0 (91 days)
Durack and Weiqing (1998)	270–398	1.23 - 2.5	0.61-0.82	-	982-1185 (DD)	1.0-6.0
	137-380	-	0.48-0.70	1.48 - 2.50	541-1003 (DD)	3.0-15.0 (77 days)
Kearsley and Wainwright (2001)	Cement-fly ash replacement 193-577	-	0.6-1.17	-	1000-1500	2.0-18.0
Jones and McCarthy (2005)	500	1.5-2.3	0.3	-	1400-1800	10.0-26.0
	500	-	0.65-0.83	1.15 - 1.77	1400-1800	20.0-43.0
Nambiar and Ramamurthy (2006)	Cement-sand mix (coarse)	With filler-cement ratio varied from 1 to 3 and fly ash replacement for sand varied from 0% to 100%			800-1350 (DD)	1.0-7.0
	Cement-sand mix (fine)					2.0-11.0
	Cement-sand-fly ash mix				650-1200 (DD)	4.0-19.0

** S/C: sand–cement ratio; F/C: fly ash–cement ratio; W/C: water–cement ratio; DD: dry density*

When cement is combined with silica fume [5] and fly ash, higher compressive strength is achieved in the long term, owing to their pozzolanic reaction and filler characteristics, with a more marked effect at high foamcrete densities. [3] carried out a study on the effect of replacing large volumes of cement (up to 75% by weight) by both classified and unclassified fly ash on strength of foamcrete. They found that up to 67% of the cement could be replaced with ungraded and graded fly ash without any significant reduction in compressive strength. The results signify that the compressive strength of foamcrete is principally a function of dry density, and foamcrete mixes with high fly ash content needed a longer time to reach their maximum strength which was observed to be higher than that attained using only cement.

In terms of the influence of fillers on strength of foamcrete, better strength is obtained when finer sand is used. For a given density, the mix with fine sand results in higher strength than the mix with coarse sand and the variation is higher at higher density. This higher strength-density ratio is credited to the moderately uniform distribution of pore in foamcrete with fine sand, while the pores were larger and irregular for mixes with coarse sand (Nambiar and Ramamurthy, 2006). Similar behaviour was observed when sand was replaced by fine fly ash.

[14] performed an extensive experimental exploration into the effect of utilization of unprocessed, run-of-station, low-lime fly ash in foamcrete, as a substitution for sand on the rheological, strength development and permeation/durability properties for foamcrete with plastic densities ranging between 1000 and 1400 kg/m^3. They found that the use of fly ash in foamcrete considerably benefited the compressive strength growth, mainly after 28 days. At a known age, the fly ash coarse concretes were up to 6 times stronger than equivalent sand concretes.

The enhancement of strength with fly ash as filler is not pronounced at lower density range especially at earlier ages. This is due to the fact that at lower density range, the foam volume controls the strength rather than the material properties [15]. The utilization of lime, demolition fines, recycled glass as fine aggregate has slight or no effect on compressive strength of foamcrete, while some decrease in strength was reported when crumb rubber, used foundry sand, china clay sand and quarry fines were used.

The compressive strength of foamcrete decreases with an increase in pore diameter for dry density of foamcrete between 500 and 1000 kg/m^3. Nevertheless for densities higher than 1000 kg/m^3, as the air-pores are far apart to have an influence on the compressive strength, the composition of the paste determines the compressive strength [6]. The type of surfactant (foaming agent) also has major effect on the compressive strength of foamcrete. An increased of strength up to 70% was found with the used of protein based foaming agent rather than synthetic foaming agent [11].

In terms of curing regime, autoclaving increases the compressive strength. [10] carried out an investigation to produce cost-effective mix for foamcrete by optimising the amount of sand in foamcrete mix by using different sand-cement ratio and curing conditions. In this study, a series of foamcrete of four different densities ranging from 1300 to 1600 kg/m^3 was fabricated using the appropriate mix proportions and a series of sand-cement ratios varying from zero to 2.0 for each series of density was attempted. Hamidah et al. found that water cured samples of foamcrete attained higher strength than those cured in air.

4.4. Flexural and tensile strength of foamcrete

The ratio of flexural strength to compressive strength of foamcrete is in the range of 0.06–0.10 and this ratio was also found to reduce with increasing water-cement ratios and decreasing densities [13]. The splitting tensile strengths of foamcrete mixes are higher for mixes with sand than those with fly ash. This is attributed to the improved shear capacity between sand particles and the paste phase [16].

The introduction of polypropylene fibers in foamcrete has been reported to improve the tensile and flexural strength of foamcrete, provided this does not affect the fresh concrete behavior and self-compaction [17].

4.5. Modulus of elasticity of foamcrete

As a porous material, the static modulus of elasticity of foamcrete is expected to be considerably lower than that of normal weight concrete for dry densities between 500 and 1500 kg/m^3 with values typically varying from 1.0 to 8.0 kN/mm^2, respectively [18].

Foamcrete mix containing fly ash as fine aggregate is reported to show lower modulus of elasticity value than that of foamcrete with sand. [18] reported that the utilization of polypropylene fibers in foamcrete mix could enhance the value of modulus of elasticity of foamcrete between two and four times. They proposed two relationships to predict the modulus of elasticity of foamcrete as follows:

Sand as fine aggregate $E_c = 0.42 f_c^{1.18}$ .... (3)

Fly ash as fine aggregate $E_c = 0.99 f_c^{0.67}$ .... (4)

where E_c is the modulus of elasticity (kN/mm^2) and f_c is the compressive strength (N/mm^2).

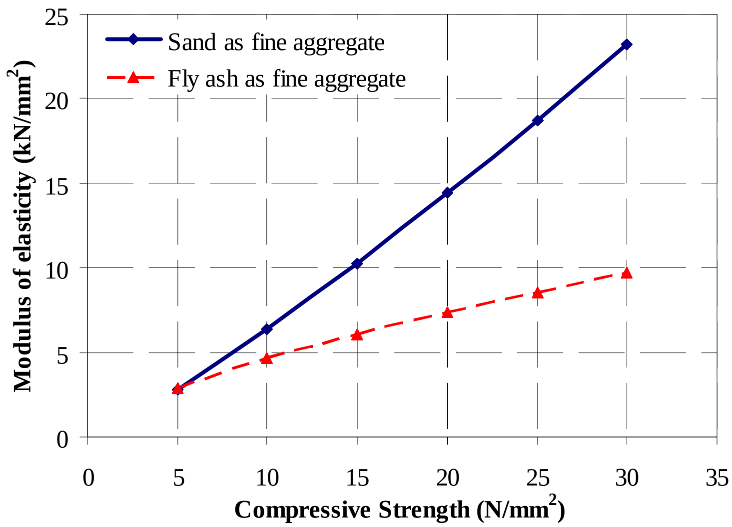

Figure 2. Modulus of elasticity and compressive strength relationship of foamcrete

Figure 2 shows a plot of modulus of elasticity against compressive strength based on Equation 3 and Equation 4. From Figure 2, it can be seen that for the same compressive strength (f_c), sand as aggregate gives higher modulus of elasticity values compared to fly ash aggregate. This difference is attributed to the high amount of fine aggregate in sand mix compared to fly ash mix, which contains completely paste with no aggregate [19].

4.6. Thermal properties of foamcrete

The cellular microstructure of foamcrete provides it with low thermal conductivity. The thermal conductivity of foamcrete typically is 5 to 30% of that of normal weight concrete and range from between 0.1 and 0.7 W/mK for dry density values of 600 to 1600 kg/m^3 respectively [18,20]. In practical terms normal weight concrete would have to be 5 times thicker than foamcrete ones to achieve similar thermal insulation [21].

The thermal conductivity of foamcrete with 1000 kg/m^3 density is reported to be one-sixth the value of typical cement-sand mortar [22]. Since foamcrete is made by injecting air into a cement based mixture, the density of foamcrete is directly a function of the air inside foamcrete. Expectedly, the density of foamcrete should play an important role in determining its thermal properties. A reduction in foamcrete density by 100 kg/m^3 results in a lessening in its thermal conductivity by 0.04 W/mK [23].

In addition to use more air to reduce the thermal conductivity of foamcrete, it is possible to reduce the thermal conductivity of foamcrete by using pulverized fuel ash. Reduction in thermal conductivity by 12-38% was attained with the introduction of 30% pulverized fuel ash in the mix compared to the foamcrete with only Portland cement SEM1 as binder material [24]. This was attributed to the lower density of fly ash particles.

4.7. Freeze thaw resistance

Foamcrete does not endure extensively when exposed to a freeze-thaw cycle [20]. Even after several harsh freeze/thaw cycles of -18 to 200°C, foamcrete with dry densities between 800 kg/m^3 and 1400 kg/m^3 has been proven to exhibit very good freeze/thaw resistance [25]. Both cement-fly ash and cement-sand mixes of dry density of 1400 kg/m^3 showed good freeze/thaw resistance [26]. This is due to the cellular structure in the foamcrete where the hollow voids provide the additional space and the volume required for the expansive forces during freezing in the foamcrete. However, in the same study, it was found that the performance of a denser mix (1800 kg/m^3) was much poorer which was attributed to the lower void content.

4.8. Fire Resistance

The fire resistance of foamcrete is excellent; at low temperatures it is better than normal weight concrete in terms of the proportional loss in strength [21]. But when exposed to high temperatures, it suffers from excessive drying shrinkage [4]. Foamcrete containing hydraulic cement with an Al2O3/CaO ratio higher than two could withstand temperatures as high as 1450°C without showing any sign of damage [23]. In addition, foamcrete has been found to be incombustible, and in a test on foamcrete slabs with 100mm thickness, standard fire resistance of 2 ½ hours and 3 ¾ hours for 1250 kg/m^3 and 930 kg/m^3 oven dry densities respectively was established based on thermal insulation [18].

5. Conclusions

The review presented in paper clearly indicates that most of the investigations on foamcrete so far have focused on its ambient temperature properties only. Among these, the majority are about mechanical properties of foamcrete with only a very few on its thermal properties. Quantitative information on fire resistance performance is extremely sparse. Nevertheless the reviewed literature does give some useful data of foamcrete mechanical and thermal properties at ambient temperature which can be used as the basis for further research.

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Addresses:

- Senior Lecturer, Dr. Md Azree Othuman Mydin, School of Housing, Building and Planning, Universiti Sains Malaysia, 11800, Penang, Malaysia, azree@usm.my
- Senior Lecturer, Dr. Norizal Md Noordin, School of Housing, Building and Planning, Universiti Sains Malaysia, 11800, Penang, Malaysia, norizal@usm.my