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A classification of studies on properties of foam concrete

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ABSTRACT

Though foam concrete was initially envisaged as a void filling and insulation material, there have been renewed interest in its structural characteristics in view of its lighter weight, savings in material and potential for large scale utilization of wastes like fly ash. The focus of this paper is to classify literature on foam concrete in terms of constituent materials (foaming agent, cement and other fillers used), mix proportioning, production methods, fresh and hardened properties of foam concrete. Based on the review, the following research needs have been identified: (i) developing affordable foaming agent and foam generator, (ii) investigation on compatibility between foaming agent and chemical admixtures, use of lightweight coarse aggregate and reinforcement including fibers, (iii) durability studies, and (iv) factors influencing foam concrete production viz., mixing, transporting and pumping.

1. Introduction

Foam concrete is either a cement paste or mortar, classified as lightweight concrete, in which air-voids are entrapped in mortar by suitable foaming agent. It possesses high flowability, low self-weight, minimal consumption of aggregate, controlled low strength and excellent thermal insulation properties. By proper control in dosage of foam, a wide range of densities (1600–400 kg/m^3) of foamed concrete can be obtained for application to structural, partition, insulation and filling grades. Although the material was first patented in 1923 [1], its construction applications as lightweight non- and semi-structural material are increasing in the last few years. The first comprehensive review on cellular concrete was presented by Valore [1,2] in 1954 and a detailed treatment by Rudnai [3] and Short and Kinniburgh [4] in 1963, summarising the composition, properties and uses of cellular concrete, irrespective of the method of formation of the cell structure. Recently, Jones and McCarthy [5] have reviewed the history on use of foam concrete, constituent materials used, its properties, and construction application including some projects carried out worldwide. The functional properties like fire resistance, thermal conductivity and acoustical properties are also included in these reviews, while the data on fresh state properties, durability and air-void system of foam concrete are rather limited.

The production of stable foam concrete mix depends on many factors viz., selection of foaming agent, method of foam preparation and addition for uniform air-voids distribution, material section and mixture design strategies, production of foam concrete, and performance with respect to fresh and hardened state are of greater significance. With the above aspects in view, this paper classifies the studies on foam concrete related to its constituent materials, mix proportioning, production and fresh state and hardened properties.

2. Constituent materials

2.1. Constituents of base mix

In addition to Ordinary Portland cement, Rapid hardening Portland cement [6,7], high alumina and Calcium Sulfoaluminate [8] have been used for reducing the setting time and to improve the early strength of foam concrete. Fly ash [5,6,9–12] and ground granulated blast furnace slag have been used in the range of 30–70% and 10–50%, respectively [13,14] as cement replacement to reduce the cost, enhance consistence of mix and to reduce heat of hydration while contributing towards long term strength. Silica fume up to 10% by mass of cement has been added to intensify the strength of cement [15–17]. Alternate fine aggregates, viz., fly ash [18–20], lime [7], chalk and crushed concrete [21], incinerator bottom ash, recycled glass, foundry sand and quarry finer [22], expanded polystyrene and Lytag fines [23,24] were used either to reduce the density of foam concrete and/or to use waste/recycled materials. Concrete with densities between 800 and 1200 kg/m^3 have been produced using lightweight coarse aggregate in foamed cement matrix [25].

The water requirement for a mix depends upon the composition and use of admixtures and is governed by the consistency and stability of the mix [26]. At lower water content, the mix is too stiff causing bubbles to break while a high water content make the mix too thin to hold the bubbles leading to separation of bubbles from the mix and thus segregation [20]. Water–cement ratio used

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ranges from 0.4 to 1.25 [15,27]. Though super plasticisers are also sometimes used [28], its use in foamed concrete can be a possible reason for instability in the foam [11] and hence compatibility of admixtures with foam concrete is of importance.

Chopped polypropylene fibers of 12 mm length in the dosage range of 1–3 kg/m^3 has been reported to enhance the shear behaviour of foam concrete equivalent to that of normal concrete. Also the usage of fibers is reported to mitigate brittleness, while reducing its weight and cost [5,29,30]. Optimum combinations of strength, ductility, density, workability and also cost can be obtained by selecting a suitable fiber type, air content and w/c ratio of base mortar [31].

2.2. Foam

A description of commonly used natural material-based and synthetic foaming agents have been presented by Valore [1], Taylor [32], Perez and Cortez [33], Laukaitis et al. [34], Park et al. [35]. Most of the earlier studies have used proprietary foaming agents, viz., Neopar [36,37], Mearlcrete [38], Elastizell [39,40], and Foam tech [6,41–43]. Foam concrete is produced either by pre-foaming method or mixed foaming method. Pre-foaming method comprises of producing base mix and stable preformed aqueous foam separately and then thoroughly blending foam into the base mix. In mixed foaming, the surface active agent is mixed along with base mix ingredients and during the process of mixing, foam is produced resulting in cellular structure in concrete [16]. The foam must be firm and stable so that it resists the pressure of the mortar until the cement takes its initial set and a strong skeleton of concrete is built up around the void filled with air [44]. The preformed foam can be either wet or dry foam. The wet foam is produced by spraying a solution of foaming agent over a fine mesh, has 2–5 mm bubble size and is relatively less stable. Dry foam is produced by forcing the foaming agent solution through a series of high density restrictions and forcing compressed air simultaneously into mixing chamber. Dry foam is extremely stable and has size smaller than 1 mm, which makes it easier for blending with the base material for producing a pump able foam concrete [45]. Viscosity of liquid phase, surface effects such as Gibbs and Marangoni effects, disjoining pressure between adjacent interfaces due to adsorption of ionic and non-ionic surfactants and polymers and concentration of foaming agents are some of the factors influencing foam stability as identified by various researchers [46–50].

3. Proportioning and preparation of foam concrete

Often trial and error process is adopted to achieve foam concrete with desired properties [51]. For a given mix proportion and density, a rational proportioning method based on solid volume calculations was proposed by McCormick [38]. Based on this work, the design aid of ACI 523-1975 [52] relates plastic density and compressive strength, using which the cement content and water–cement ratio can be chosen for a given strength and density. ASTM C 796-97 [53] provides a method of calculation of foam volume required to make cement slurry of known water–cement ratio and target density. Kearsley and Mostert [54] have proposed a set of equations (density and volume of foam concrete), which are written in terms of the mixture composition, for calculating the foam volume and cement content. For a given 28-day compressive strength, filler–cement ratio and fresh density, typical mix design equations of Nambiar and Ramamurthy [55] determines mixture constituents viz., percentage foam volume, net water content, cement content and percentage fly ash replacement. Most of the methods proposed, help in calculation of batch quantities if the mix proportions are known. Even though the strength of foam concrete depends on its density, for a given density, the strength can be increased by changing the constituent materials. Also, for a given density, the foam volume requirement depends on the constituent materials [55]. Hence for a given strength and density requirement, the mix design strategy should be able to determine the batch quantities.

Pre-formed foaming is preferred to mix-forming technique due to the following advantages: (i) lower foaming agent requirement and (ii) a close relationship between amount of foaming agent used and air content of mix [1,16]. Most common types of mixers (tilt drum or pan mixer used for concrete or mortar) are suitable for foam concrete. The type of mixer and batching and mixing sequences of foam concrete depends upon pre-formed foam method or mix-foaming method [26].

4. Properties of foam concrete

Table 1 summarizes the fresh and hardened properties studied by researchers. The hardened properties are classified into physical (drying shrinkage, density, porosity and air-void system, sorption), mechanical (compressive and tensile strength, modulus of elasticity, prediction models), durability properties and functional characteristics (thermal conductivity, acoustical properties and fire resistance).

4.1. Fresh state properties

As foam concrete cannot be subjected to compaction or vibration the foam concrete should have flowability and self-compactability. These two properties are evaluated in terms of consistency and stability of foam concrete, which are affected by the water content in the base mix, amount of foam added along with the other solid ingredients in the mix [74].

4.1.1. Consistency

Flow time using marsh cone and flow cone spread tests are adopted to assess the consistency of foam concrete [10]. These measurements were also related to rheology and it was observed that coarse fly ash as filler exhibited 2.5 times higher spread compared to cement–sand mix. This enhanced consistence and rheology is attributed to difference in particle shape and size of fine aggregate. When replacing sand with fine fly ash by mass, the consistency of the mix is reduced due to higher fines content. Hence to satisfy the consistency requirement, an increase in water–solids ratio is required with an increase in fly ash replacement level. However fly ash mixes were also reported to affect foam stability, necessitating larger foam volume to achieve the design plastic density, which was attributed to the high fluid consistency in the base mix and high residual carbon in the ash [10]. The consistency reduces with an increase in volume of foam in the mix, which may be attributed to the (i) reduced self-weight and greater cohesion resulting from higher air content [26] and (ii) adhesion between the bubbles and solid particles in the mix increases the stiffness of the mix.

4.1.2. Stability

The stability of foam concrete is the consistency at which the density ratio is nearly one (the measured fresh density/design density), without any segregation and bleeding [20,74]. This ratio is higher than unity at both lower and higher consistencies due to either stiffer mix or segregation. The stability of test mixes can also be assessed by comparing the (i) calculated and actual quantities of foam required to achieve a plastic density within 50 kg/m^3 of the design value and (ii) calculated and actual w/c ratios. The additional free water contents resulting from the foam collapse

Table 1
Tabulation showing literature and properties of foam concrete investigated.

Author(s) (Year)	Ingredients	Fresh state properties	Physical and mechanical properties						Durability	Functional properties
			Shrinkage	sorption	Porosity	Density	Strength	Models		
Valore [1,2]	C/L/CM		√	√	√	√	√			Thermal, fire and acoustical properties
McCormick [38]	CM					√	√	√		
Hoff [56]	C				√		√	√		
Richard [39,40]	C					√	√			Thermal properties, Cryogenic applications
Prim and Wittmann [57]	CM			√	√					
Tada and Nakano [58]	CM			√	√					
Tada [59]	C					√	√	√		Optimum acoustical performance design
Tam et al. [60]	CM						√			
Regan and Arasteh [25]	LWA		√			√	√			
Karl and Worner [26]	–	√								
Hunaiti [36,37]	CM						√			
Kearsley [15,29]	CM		√				√	√		
Kearsley and Mostert [30]	C/CF					√	√			Thermal properties
Kearsley and Booyens [61]	–			√			√		√	
Durack and Weiqing [19]	CM/ CFM				√		√	√		
Kearsley and Visagie [62]	C/CF				√ (AV)	√	√			
De Ross and Morris [7]	C/CF/L		√				√			Thermal conductivity
Nehdi et al. [51]	–					√	√	√		
Jones [28]	CM		√				√		√	
Turner [8]	CM	√								
Kyle [63]	CM						√			
Kearsley and Wainwright [6,41–43]	C/CF			√	√	√	√			
Jones and Giannakou [64,65]	–									Energy efficient foundation – thermal analysis
Madjoudj et al. [66]	–			√						
Jones et al. [18]	CM	√	√				√			
Tikalsky et al. [67]	CM								√	
Kearsley and Mostert [68]	CM/CFM									Fire resistance, use in refractory
Proshin et al. [69]	–									Thermal protective foam concrete & energy
Jones and McCarthy [5]	CM	√	√				√			Comparison of Thermal conductivity
Jones and McCarthy [9]	CM		√				√	√	√	
Wee et al. [14]	CG				√(AV)		√			
Laukaitis and Fiks [70]	CM				√					Comparison of acoustical properties
Nambiar and Ramamurthy [20,56,71–74]	CM/CFM	√	√	√	√(AV)	√	√	√		

CM – cement mortar, C – neat cement, L – lime, CFM – cement fly ash mortar, CF – cement with fly ash replacement, ac – autoclaving, mc – moist curing, LWA – lightweight aggregate, CG – cement with GGBS replacement, and AV – air-void characterization (system).

corresponded to an increase in actual w/c ratio [11]. Thus the consistency of the base mix to which foam is added is an important factor, which affects the stability of mix. This consistency reduces considerably when foam is added and depends on the filler type also.

Hence there is a need for determining the water–solids ratio, which would satisfy both stability and consistence of the mix. Regression equations based on the experimental results, for predicting the spread flow value of foam concrete, knowing the proportion of the other ingredients, will help in arriving at this water content for the production of a stable and workable foam concrete mix. For typical materials used, an appropriate workability value has been arrived at as 45% of spread at which a foam concrete mix of good stability and consistency can be produced [74].

4.2. Physical properties

4.2.1. Drying shrinkage

Foam concrete possesses high drying shrinkage due to the absence of aggregates, i.e., up to 10 times greater than those observed on normal weight concrete [2,18]. Autoclaving is reported to reduce the drying shrinkage significantly by 12–50% of that of moist-cured concrete (due to a change in mineralogical compositions) and is essential if the products are required within acceptable level of strength and shrinkage [1,75]. The shrinkage of foam concrete reduces with density [18,58,75,76], which is attributed to the lower paste content affecting the shrinkage in low-density mixes.

In a comparative study on the shrinkage behaviour with sand and fly ash as filler, foam concrete with sand exhibited smaller drying shrinkage which is attributed to the higher shrinkage restraining capacity of sand as compared to fly ash particles [18]. It is reported that lightweight aggregate could be used to reduce the shrinkage of foam concrete [25,77].

4.2.2. Air-void systems

The pore structure of cementitious material, predetermined by its porosity, permeability and pore size distribution, is a very important characteristic as it influences the properties such as strength and durability. The pore structure of foam concrete consists of gel pores, capillary pores as well as air-voids (air entrained and entrapped pores) [78]. As foam concrete being a self-flowing and self-compacting concrete and without coarse aggregate, the possibility of entrapped air is negligible. The air-voids in the foam

Table 2
Empirical models for density determination.

Reference	Equation	Remarks
ASTM C 796-97 [53]	Dry density = $(W_c + 0.2W_c)/V_{batch}$	W_c and V_{batch} are weight of cement and volume of batch, respectively
ACI committee 523 [52]	Dry density = $1.2C + A$	C and A are weight of cement and aggregate in kg per cubic meter of concrete
Kearsley [29]	$\gamma_{dry} = 0.868\gamma_{cast} - 55.07$	Casting density range of 700–1500 kg/m^3. Cement–fly ash mixture of varying fly ash–cement ratio (F/C = 0–4)

concrete can be characterized by a few parameters like volume, size, size distribution, shape and spacing between air-voids.

The air-void distribution is one of the most important micro-properties influencing strength of foam concrete. Foam concrete with narrower air-void distributions shows higher strength. The use of fly ash as filler helps in achieving more uniform distribution of air-voids by providing uniform coating on each bubble and thereby prevents merging of bubbles. At higher foam volume, merging of bubbles results in wide distribution of void sizes leading to lower strength [71,78]. In addition to the air-void size and its distribution, the compressive strength of foam concrete is also be influenced by the void/paste ratio, spacing of air-voids, number (frequency) of air-voids. Because of the uniform shape (characterized by shape factor) of air-voids, its influence on strength is negligible [14,62,71]. At the same time, for gas concrete, another type of aerated concrete, the expansion of concrete during gas formation result in the development of ellipsoidal oriented pores [79]. In a study on air-void system of foam concrete made of cement–ground granulated blast furnace slag mixture, for achieving a high strength-to-weight ratio, an air-void system with a spacing factor, air-void size and air content of 0.04 mm, 0.12 mm and 42%, respectively, were reported to be optimal [14]. Finer filler material helps in uniform distribution of air-voids.

The ratio of connected pores to total pores in foam concrete is lower resulting in lower air permeability compared to gas concrete [70], which leads to comparatively lower sound and water absorption in foam concrete. The entrained air-voids create an increasingly tortuous path for the capillary flow in proportion to foam volume and dampen the transport phenomenon. Higher air-void volume results in lesser pore wall thickness and paste volume causing lower shrinkage [58]. The larger pores in aerated concrete can be treated as aggregate of zero density and a transition zone exists in the void-paste interface of such concrete analogous to the one in aggregate–paste interface of normal concrete [80]. Thus understanding the air-void system is essential for producing foam concrete with a high strength-to-weight ratio with advantageous properties.

4.2.3. Density

Density can be either in fresh or hardened state. Fresh density is required for mix design and casting control purposes. A theoretical equation for finding fresh density may not be applicable as there can be scatter in the results caused by a number of factors including continued expansion of the foam after its discharge, loss of foam during mixing [25]. Many physical properties of foam concrete related to/depend upon its density in hardened state. While specifying the density, the moisture condition needs to be indicated as the comparison of properties of foam concrete from different sources can have little meaning without a close definition of the degree of dryness [2]. As the properties are expressed in terms of dry density, the relationships proposed in literature between dry and fresh density are summarized in Table 2.

McCormick [38] studied the effect of types of fine aggregate, aggregate gradation, type of foam and sand–cement ratio on the wet density of foam concrete and reported that wet densities within about 5% of the design densities can be achieved by using solid volume calculations. The cement–sand based non-autoclaved preformed foam concrete has relatively higher density and higher requirement of cement content. Greater the proportion of aggregate, higher will be the density. Compared to a product based on sand and cement, it is observed that replacement of sand with fly ash help in reducing the density with an increased strength [19]. Alternately, to achieve a particular density of foam concrete, use of fly ash results in a reduction in foam volume requirement due to its lower specific gravity [55], thereby resulting in higher strength.

4.3. Mechanical properties

4.3.1. Compressive strength

Table 3 presents an overview of compressive strength of foam concrete for various mixture composition and densities reported in literature. The compressive strength decreases exponentially with a reduction in density of foam concrete [15]. The specimen size and shape, the method of pore formation, direction of loading, age, water content, characteristics of ingredients used and the method of curing are reported to influence the strength of cellular concrete in total [2]. Other parameters affecting the strength of foam concrete are cement–sand and water–cement ratios, curing regime, type and particle size distribution of sand and type of foaming agent used [45,83]. For dry density of foam concrete between 500 and 1000 kg/m^3, the compressive strength decreases with an increase in void diameter. For densities higher than 1000 kg/m^3, as the air-voids are far apart to have an influence on the compressive strength, the composition of the paste determines the compressive strength [78]. It has been reported that small changes in the water–cement ratio does not affect the strength of foam concrete as in the case of normal weight concrete [11]. At higher water–cement ratios (within the consistency and stability limit) an increase in strength is observed with an increase in water–cement ratio [7,60], just opposite to the trend usually noted for conventional concrete/mortar where the entrapped air content is only a few percentage by volume. It has been concluded by Tam et al. [60] that (i) the strength of moist-cured foam concrete depends on water–cement ratio and air–cement ratio and (ii) the combined effect should be considered when volumetric composition of air-voids approaches that of water voids.

A study on the effect of replacing large volumes of cement (up to 75% by weight) with both classified and unclassified fly ash on strength of foam concrete reports that up to 67% of the cement could be replaced with ungraded and graded fly ash without any significant reduction in strength [6]. The results indicate that the compressive strength of foam concrete is primarily a function of dry density, and foam concrete mixes with high fly ash content needed a longer time to reach their maximum strength which was observed to be higher than that achieved using only cement. When the cement is replaced with silica fume, higher compressive strength is obtained in the long term, due to their pozzolanic reaction and filler characteristics, with a more marked effect at high foam concrete densities.

For a given density, the mix with fine sand resulted in higher strength than the mix with coarse sand and the variation is higher

Table 3
A review of mixes used, compressive strengths and density ranges of foam concrete.

Author(s) and year	Proportion of cement kg/m^3 or composition	Ratios			Density range kg/m^3	Comp. strength (28 days)
		S/C	W/C	F/C		
McCormick [38]	335–446	0.79–2.8	0.35–0.57		800–1800	1.8–17.6
Tam et al. [60]	390	1.58–1.73	0.6–0.8		1300–1900	1.81–16.72
Regan and Arasteh [25]		0.6 (LAC/C)	0.45–0.6		800–1200	4–16
Van Deijk [24]	Cement–sand/fly ash				280–1200	0.6–10 (91-days)
ACI 523.1R-1992 [81]	Neat cement paste				240–640 (DD)	0.48–3.1
	Cement–sand mix				400–560 (DD)	0.9–1.72
Hunaiti [37]		3			1667	12.11
Kearsley and Booyens [61]	Cement–fly ash replacement				1000–1500	2.8–19.9
Durack and Weiqing [19]	270–398	1.23–2.5	0.61–0.82		982–1185 (DD)	1–6
	137–380		0.48–0.7	1.48–2.5	541–1003 (DD)	3–15 (77-days)
Aldridge [82]	Cement–sand mix				400–1600	0.5–10
Kearsley and Wainwright [6]	Cement–fly ash replacement				1000–1500	2–18
	193–577		0.6–1.17			
Tikalsky et al. [67]	Neat cement				490–660	0.71–2.07
	149–420		0.4–0.45			
	Cement–sand/fly ash				1320–1500	0.23–1.1
	57–149		0.5–0.57			
Jones and McCarthy [10]	300	1.83–3.17	0.5		1000–1400	1–2
			1.11–1.56	1.22–2.11	1000–1400	3.9–7.3
Jones and McCarthy [9]	500	1.5–2.3	0.3		1400–1800	10–26
	500		0.65–0.83	1.15–1.77	1400–1800	20–43
Nambiar and Ramamurthy [55]	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)	1–7
	Cement–sand mix (fine)				800–1350 (DD)	2–11
	Cement–sand–fly ash mix				650–1200 (DD)	4–19

S/C: sand–cement ratio; F/C: fly ash–cement ratio; W/C: water–cement ratio; LAC: lightweight aggregate content, DD: dry density.

at higher density. This higher strength to density ratio is attributed to the comparatively uniform distribution of pore in foam concrete with fine sand, while the pores were larger and irregular for mixes with coarse sand [20,38]. Similar behaviour was observed when sand was replaced with fine fly ash [55]. Compressive strength of foam concrete using fly ash, as a partial/complete replacement for filler, resulted in higher strength to density ratio [5,9,19,55]. The enhancement of strength with fly ash as filler is not pronounced at lower density range (higher% of foam volume) especially at lower ages. This is due to the fact that at lower density range it is the foam volume that controls the strength rather than the material properties [55]. The combined effect of high water retentivity and pozzolanic activity of fly ash has been attributed to contribute to the good performance of fly ash as binder in foam concrete [12]. Mixes containing expanded shale aggregate produced higher strength value than those containing sand as aggregate for the same wet density. The use of lime, demolition fines, recycled glass as fine aggregate has little or no effect on compressive strength, while some reduction in strength has been noted when crumb rubber, used foundry sand, china clay sand and quarry fines were employed [7,22].

In terms of curing regime, autoclaving increases the compressive strength. In general, compressive strength of water–cured foamed concrete is reported to be higher than that cured in air [83]. But higher strengths are reported for humid air curing at a temperature around 40 °C as compared to normal water-cured specimens [61]. The low cost of moist-curing is an attractive and viable alternative in many applications [60], though the strength development is rather slow. Autoclaving is generally used for pre-cast structural cellular concrete elements.

4.3.2. Flexural and tensile strengths

The ratio of flexural strength to compressive strength of cellular concrete is in the range of 0.25–0.35 [2]. Splitting tensile strengths of foam concrete are lower than those of equivalent normal weight and lightweight aggregate concrete with higher values observed for mixes with sand than those with fly ash. This increase is attributed to the improved shear capacity between sand particle and the paste phase [9]. Use of Polypropylene fibers has been reported to enhance the performance with respect to tensile and flexural strength of foam concrete, provided it is not affecting fresh concrete behaviour and self-compaction [30].

4.3.3. Modulus of elasticity

The static modulus of elasticity of foam concrete is reported to be significantly lower than that of normal weight and lightweight concrete, with values typically varying from 1.0 to 8.0 kN/mm^2, for dry densities between 500 and 1500 kg/m^3, respectively [9]. The E-values of normal weight concrete exhibited values up to four times larger than that of equivalent strength foam concrete. Foam concrete with fly ash as fine aggregate is reported to exhibit lower E-value than that of foam concrete with sand. This variation is attributed to the high amount of fine aggregate in sand mix compared to fly ash mix, which contains entirely paste with no aggregate [28]. Use of polypropylene fibers has been observed to increase the E-value between two and four times [9]. At low temperature, an increase in compressive strength is accompanied by an increase in stiffness, which was observed to be more in higher density range [40]. A few relations reported for Modulus of Elasticity with density and compressive strength are shown in Table 4.

4.4. Strength prediction models

A few researchers developed expressions for predicting strength of foam concrete, which contain large amount of air-voids. Hoff

Table 4
Relations for modulus of elasticity (E) of foam concrete.

Author(s) and year	Relationship	Remarks
Tada [49]	$E = 5.31 * W - 853$	Density from 200 to 800 kg/m^3
McCormick [38]	$E = 33\, W^{1.5}\sqrt{f_c}$	Pauw's equation
Jones and McCarthy [9]	$E = 0.42 f_c^{1.18}$	Sand as fine aggregate
	$E = 0.99 f_c^{0.67}$	Fly ash as fine aggregate

W – density of concrete (kg/m^3), f_c – compressive strength (N/mm^2), E (kN/mm^2).

[56] proposed a single strength-porosity model for foam concrete with cement paste by combining space occupied by evaporable water and air-voids. Strength prediction models on foam concrete proposed by Kearsely and Wainwright [42] states that Hoff's model can be effectively used to predict the compressive strength of foam concrete at different ages and different densities prepared from cement paste with and without fly ash replacement. These strength-porosity models based on cement paste cannot be directly extended to foam concrete with fillers like sand/fly ash.

For limited set of operating conditions Tam et al. [60] reported a model for strength of foam concrete based on Feret's equations. This equation was improved by incorporating the degree of hydration through Power's gel-space ratio concept. Based on the same concept, strength prediction models for foam concrete made of cement mortar (with sand and fly ash as fine aggregate) was proposed by Durack and Weiqing [19] for mixes of lower density ranges. For a range of mixture compositions but with wide range of densities, Nambiar and Ramamurthy [73] have proposed similar relations based on Balshin's model and Power's gel-space ratio concept. Out of these, model based on Balshin stands out as (i) correlated well with measured values (ii) ease in application since it employs composition of constituents and easily measurable parameters. Also Balshin's equation provides a good fit to the plot of compressive strength against total porosity for (i) slate based autoclaved aerated concretes [84], (ii) at all ages of foam concrete made of cement paste containing high percentage of ash [42], and (iii) foam concrete containing high amount of fly ash as replacement to sand [73].

As there is a possibility of change in actual foam volume in hardened stage due to loss of foam in mixing and expansion of the foam after its discharge [25], dry density cannot be used as a basis for aiming at the exact composition of foam concrete mixes. Hence it would be preferable to include fresh density in such models, which can easily be measured in the field. Otherwise, models relating dry density and fresh density as given in Table 2 may be used for arriving the fresh density for a specified dry density. For evaluating the modulus of elasticity from density and strength, the models presented in Table 4 may be used.

Empirical models for predicting the strength and density of foam concrete from mixture composition details like filler–cement ratio, fly ash percentage as filler and foam volume, through statistically designed experiments (Response Surface Methodology) have been developed [55]. These models can act as a guideline in the mixture proportioning of foam concrete.

4.5. Durability of foam concrete

4.5.1. Permeation characteristics

Water absorption: Water absorption of foam concrete decreases with a reduction in density, which is attributed to lower paste volume phase and thus to the lower capillary pore volume. The water absorption of foam concrete is mainly influenced by the paste phase and not all artificial pores are taking part in water absorption, as they are not interconnected [20,41]. Expressing water absorption as percentage by mass can lead to misleading results when foam concrete is concerned because of larger differences in density. The oxygen and water vapour permeability of foam concrete have been observed to increase with increasing porosity and fly ash content [61]. Permeability coefficient of lightweight foamed concrete is proportional to unit weight and inversely proportional to pore ratio [16].

Sorptivity: The moisture transport phenomenon in porous materials has been defined by an easily measurable property called sorptivity (absorbing and transmitting water by capillarity), which is based on unsaturated flow theory [85,86]. It has been shown that the water transmission property can be better explained by sorptivity than by permeability. Sorptivity of foam concrete is reported to be lower than the corresponding base mix and the values reduce with an increase in foam volume [65,66,72]. Also, the sorption characteristic of foam concrete is observed to depend upon the filler type, pore structure and permeation mechanisms. A comparison the sorptivity of foam concrete with sand and fly ash as aggregate exhibited that the mixes with fly ash resulted in marginally higher sorptivity than mixes with sand [10].

4.5.2. Resistance to aggressive environment

Foam concrete mixture designed at low density taking into consideration of depth of initial penetration, absorption and absorption rate, provided good freeze-thaw resistance [28,67]. Sulphate resistance of foam concrete, studied by Jones and McCarthy [10] for 12 months, reveals that foam concrete has good resistance to aggressive chemical attack. A study on accelerated carbonation of foam concrete by Jones and McCarthy [9] indicate that lower density concrete appears to carbonate at a relatively higher rate. Comparing the performance of mixes with sand and fly ash, mixes with fly ash exhibited higher carbonation than that with sand. An accelerated chloride ingress tests suggested that foam concrete performance is equivalent to that of normal concrete, with enhanced corrosion resistance at lower density [61]. The cell-like structure of foam concrete and possible porosity of cell wall do not necessarily make the foam concrete less resistant to penetration of moisture than dense concrete; the air-voids appears to act as a buffer preventing rapid penetration.

4.6. Functional characteristics

4.6.1. Thermal insulation

Foam concrete has excellent thermal insulating properties due to its cellular microstructure. The thermal conductivity of foam concrete of density 1000 kg/m^3 is reported to be one-sixth the value of typical cement–sand mortar [21]. A study by Giannakau and Jones [65] exploring the potential of foam concrete to enhance the thermal performance of low rise building has shown that the foam concrete ground supported slab foundation is possessing better thermal insulation and lower sorptivity properties while producing satisfactory strength.

Comparison with normal concrete: The thermal conductivity values are 5–30% of those measured on normal weight concrete and range from between 0.1 and 0.7 W/mK for dry densities values of 600–1600 kg/m^3, reducing with decreasing densities [5]. Thermal insulation of brick wall can be increased by 23% when inner leaf is replaced with foamed concrete of unit weight 800 kg/m^3 [32].

Effect of density variation on thermal conductivity: Insulation is more or less inversely proportional to density of concrete [27]. A decrease of concrete dry density by 100 kg/m^3 results in a reduction of thermal conductivity by 0.04 W/mK of lightweight aggregate foam concrete [77]. Altering the mortar/foam ratio affects density which has enormous impact on insulation capacity [24].

Influence of fly ash, light weight aggregate: 12–38% reduction in thermal conductivity of foam concrete with 30% PFA (Pulverized Fuel Ash) as compared to mixes with only Portland cement as binder is attributed to the lower density and cenospheric particle morphology of fly ash particles, which increases the heat flow path [65]. Jones and McCarthy [11] report that foam concrete exhibited typical thermal conductivity between 0.23 and 0.42 W/mK at 1000 and 1200 kg/m^3 dry densities. The replacement of cement by finer fly ash (30% by weight of cement) helped to reduce temperature development during heat of hydration. The use of lightweight aggregates with low particle density in combination with artificially introduced air-voids in the mortar matrix has been observed to be advantageous in reducing thermal conductivity [77]. By moderate filling of porous mortar with polystyrene granules, foam concrete of density range 200–650 kg/m^3 with thermal conductivity 0.06–0.16 W/mK could be produced [69].

Effect of temperature on thermal conductivity: Thermal insulation is reported to improve with a reduction in temperature [40]. While studying the potential of cellular concrete for load bearing insulations for cryogenic applications, Richard et al. [39] reviewed the thermal and mechanical characteristics of foam concrete. Influence of temperature variations from 22 to −196 °C is reported for selected densities between 640 and 1440 kg/m^3. An apparent reduction of 26% in thermal conductivity of foam concrete has been reported when temperature was lowered from 22 to −196 °C. Based on the thermal performance requirements for buildings, an optimum material design has been proposed by Tada [59].

4.6.2. Acoustical properties

Valore [2] states that cellular concrete does not possess unique or significant sound insulation characteristics. Foamed concrete is stated to be less effective than dense concrete in resisting the transmission of air-borne sound [32], because the Transmission Loss (TL) of air-borne sound is dependant on mass law, which is a product of frequency and surface density of the component. Tada [59] attributed the TL to the rigidity and internal resistance of the wall, in addition to the mass law and gives an acoustical performance design of cellular concrete based on bulk density and thickness. Sound transmission of a cellular concrete wall, over most of the audible frequency range may be higher by 2–3% as compared to normal weight concrete. While dense concrete tends to deflect sound, foam concrete absorbs it, and hence the foam concrete has higher sound absorption capacity [32].

4.6.3. Fire resistance

At high temperature the heat transfer through porous materials is influenced by radiation, which is an inverse function of the number of air–solid interfaces traversed. Hence along with its lower thermal conductivity and diffusivity, the foam concrete may result in better fire resistance properties [2]. Fire resistance tests on different densities of foam concrete indicated that the fire endurance enhanced with reductions in density. While reviewing earlier studies on fire resistance, Jones and McCarthy [9] summarise that, for lower densities of foam concrete, the proportional strength loss was less when compared to normal concrete. As compared to vermiculite concrete, lower densities of foam concrete is reported to have exhibited better fire resistance, while with higher densities, this trend is stated to be reversed [45]. Kearsley and Mostert [68] studied the effect of cement composition on the behaviour of foam concrete at high temperature and concluded that foam concrete containing hydraulic cement with an Al_2O_3/CaO ratio higher than two can withstand temperatures as high as 1450 °C without showing sign of damage.

5. Summary

Most of the investigations on foamed concrete have been confined to the evaluation of its properties rather than on the foam characteristics, which has bearing on the strength of the foamed material. Foam stability in concrete is one of the important aspects to ensure the fine and uniform texture throughout the whole hardening process. Though for the given density and strength requirement, many proportioning methods and guidelines have been proposed, as such there is no standard mix proportioning method available for foam concrete.

The water–solids ratio adopted for the mix should satisfy both stability and consistence requirements of the mix, as the consistency reduces considerably with an increase in foam volume which in turn affects the stability of the mix. The drying shrinkage strains of foam concrete were high as would be expected in a concrete with large paste phase volume. But this could be reduced by adopting autoclave method of curing, by using light weight aggregates and by partial substitution of Portland cement with fine fly ash which reduces the heat of hydration. The concrete with uniform distribution of air-void sizes, circular air-voids and optimal spacing between voids can produce foam concrete with good mechanical properties. For a given density, the compressive strength of foam concrete using fly ash as filler has high strength to density ratio than equivalent sand based foam concrete mixes and this difference increases with increase in age. However at lower density, the foam volume controls the strength rather than the material properties. Hence the compressive strength is primarily a function of density. The durability studies showed that the cell-like structure and possible porosity do not make it less resistant to penetration of aggressive ions than the densely compacted normal weight concrete. This is because the ratio of connected pores to total pores which determines the durability is lower in foam concrete. Hence it has good resistance to freeze and thaw, fire and possesses lower sorptivity, water absorption and thermal conductivity.

The need for developing affordable foaming agent and foam generator is essential to facilitate wider use of foam concrete. There is need to investigate compatibility between foaming agent and chemical admixtures, use of lightweight coarse aggregate and reinforcement including fibres, for enhancing the potential of foam concrete as a structural material. This review highlights the need for systematic investigations on the durability aspects of foam concrete with a view of evolving performance based design criteria. The difficulties encountered in the foam concrete production viz., mixing, transporting and pumping needs to be addressed as they have major influence on the fresh and hardened properties of foam concrete.

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