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Review Article

Physical and mechanical properties of foamed concrete, a literature review

Yogesh Tambe[1*], and Pravin Nemade[2]

[1] *Department of Civil Engineering, Dr. D.Y. Patil Institute of Technology, Savitribai Phule Pune University, Pune, Maharashtra, 422013 India*

[2] *Department of Civil Engineering, Maratha Vidya Prasarak Samaj's Karmaveer Adv. Baburao Ganpatrao Thakare College of Engineering, Savitribai Phule Pune University, Pune, Maharashtra, 422013 India*

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Abstract

Foamed concrete has superior rheological and thermal insulation properties along with a low density and high strength/weight ratio. Also, foamed concrete has reduced manufacturing and transportation costs compared to conventional concrete and can be utilized in structural elements. Foamed concrete significantly lowers the self-weight of the superstructure and contributes large energy savings. This review mainly focuses on the ingredients and techniques required for the production of foam concrete, mix design techniques, and the physical, functional, and mechanical properties. The key motive for this systematic quantitative literature survey was to identify research gaps in existing literature and also to provide extensive insights regarding suitable applications of cellular concrete.

Keywords: cellular or foamed concrete, fire resistance, acoustic insulation, shrinkage, porosity, capillarity, compressive strength, split tensile strength, flexural strength, young's modulus

1. Introduction

Cellular concrete is a light-weight type of concrete with density in the range 400–1800 kg/m^3, consisting gas-filled voids produced by a foaming agent added into the matrix. Foamed concrete can be utilized in structural elements with density below 1000 kg/m^3 (Suman Kumar, Deepankar Kumar, & Rudžionis, 2021). The bubbles in the mortar are due to the formation of gas (Borvorn, 2011). The major benefits of foamed concrete, when compared with conventional concrete, are reduction in self-weight, superior acoustics with thermal insulation, fire resistance, reduced costs of raw materials, and self-compacting and self-leveling behavior (Suriyaprakash, & Hameed, 2018). The cement-based lightweight panels have superior thermal insulation and mechanical characteristics, and are sustainable for energy-efficient structures (Suman Kumar, Žymantas, & Danute, 2020). Many studies have mainly focused on the production of sustainable and thermal insulating cement-based lightweight composites, which help reduce the global warming effects (Suman Kumar, Deepankar Kumar, & Rudžionis, 2021). Various territories such as the United Kingdom, the Netherlands, Germany, Brazil, Turkey, Malaysia, Saudi Arabia, Singapore and Thailand, have adopted the usage of foamed concrete in construction industry on a large scale (Mydin, & Wang, 2011). Initially in 1923 foamed concrete using OPC was patented by Axel Eriksson (Mindess, 2014). According to (Panesar, 2013), Eklund patented the Siporex variant using vapor curing in Switzerland, in 1934. In 1950, the United Kingdom invented coal slag based foamed concrete used in load-bearing structural elements. According to (S. Nandi, 2016) the Falkirk railway tunnel was constructed in Scotland in 1980, with 4500 m^3 quantity of foamed concrete having density of 1100 kg/m^3. In Thailand, aerated concrete is widely used in the construction of exterior and interior walls of buildings (Chaitongrat, & Siwadamrongpong, 2016). In the past twenty years, due to significant modifications in the raw pozzolanic materials, manufacturing tools and equipment,

*Corresponding author
Email address: yogeshtambe619@gmail.com

plasticizers and admixtures, and advanced foam producing agents the utilization of such concrete has become possible on a large scale. A comprehensive study should be carried out on the performance of cellular concrete to modify its structural applications with proper mix design code provisions. This literature review scrutinizes important aspects regarding foamed concrete development and recent modified technologies, indicating the usage of different additives/fillers to improve its characteristics and behavior. Also, we intend to assess the properties of cellular concrete in fresh and dense state to enhance its structural performance. This literature study concentrates on the functional, physical and mechanical characteristics of foam concrete with its performance. The importance of this review is in providing extensive insights regarding suitable applications of cellular concrete with novel advancements in the materials, production techniques, and mix proportions.

2. Ingredients of Foamed Concrete

Foamed concrete involves as basic ingredients mortar such as cement, sand, and water (C+S+W), plus fine aggregates (FA) needed to manufacture concrete (Figure 2).

2.1 Cement/Binder

Ordinary Portland cement (OPC) is a most suitable binder in the manufacturing of cellular concrete. The enormous increase in the consumption of energy and rising waste disposal issues have attracted research worldwide to address the waste materials for sustainable growth of economy and the society (Suman Kumar, Žymantas, & Tučkutė, 2022). Figure 1 presents a ternary diagram of various residual wastes, considering their chemical compositions. Jones, and McCarthy (2005), Nambiar, and Ramamurthy (2006) reported that cementitious materials may be responsible for attaining various characteristics of foam concrete (Table 1). For instance, silica fume strengthens the foamed concrete because of its pozzolanic behavior and qualities as filler, in a short interval of time, while according to Kearsley, and Wainwright (2001), flyash requires more time in the attainment of utmost strength of cement. The use of flyash in concrete as a substitute for cement improves the hydration due to its pozzolanic activity, by the formation of C-S-H gel (Sharipudin, Ridzuan, Noor, & Hassan, 2016). The use of industrial residual wastes is in a good agreement with requirements on compressive and flexural strength (Awang, Aljoumail, & Noordin, 2014) and with reduced cracking on using ultrafine sized particles (Pan, Duan, Li, & Collins, 2012). An excessive percentage of binder causes segregation in the cement paste (Suman Kumar, & Rudžionis, 2020). Combinations of hydrophobic silica aerogel particles (45%) and expanded glass (55%) have been incorporated as lightweight aggregates in the concrete matrix (Suman Kumar, Rudžionis, & Deepankar Kumar, 2021).

2.2 Foam agents

The foaming agent concentration affects mainly the voids' distribution and sizes, which directly affect final strength of the foamed concrete (Kuzielová, Pach, & Palou, 2016). The most familiar foaming agents are either synthetic, protein (polypeptides) based, hydrolyzed protein, resin soap, or detergents (Deijk, 1991 & Bing; Zhen, & Ning, 2011). The foaming agent with polypeptides results in a strong and compact pore structure, with increased volumetric fraction of voids, synthetic foaming agents attain low density and greater expansion (Beningfield, Gaimster, & Griffin, 2005). The type of foaming agent significantly affects the fresh and dense state properties of cellular concrete (Jones, & McCarthy, 2005). The different foaming agents used in studies are Notraite PA-1, Protein based, Vegetable protein, and EABASSOC (Hilal, & Ameer, 2015; Kurweti, & Chandrakar, 2017; Richard, & Ramli, 2013).

2.3 Plasticizers

The utilization of significant plasticizers in foamed concrete improves workability and maintains compatibility amongst the voids. Practically, a plasticizer improves the rheological characteristics of concrete mix, allowing reduction of the quantity of water without causing segregation problem. The dose of plasticizers is in the range from 0.45% to 5% by volume of the foaming agent (Jezequel, & Mathonier, 2014).

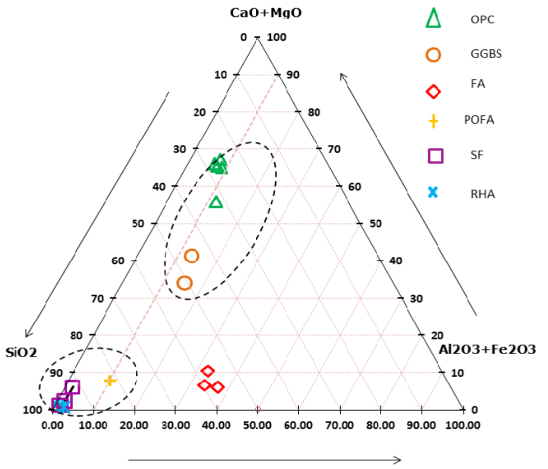

Figure 1. Ternary diagram

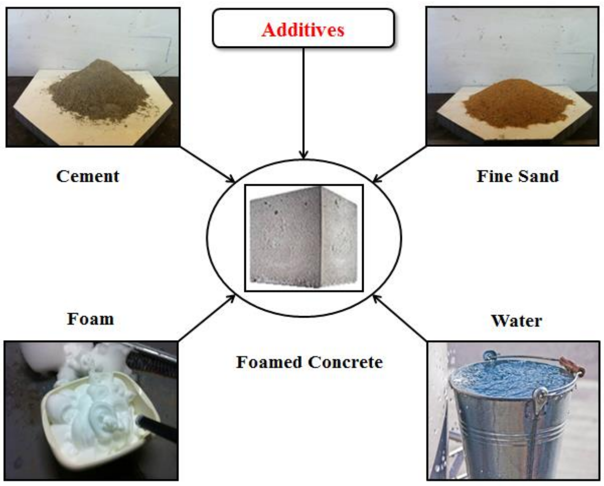

Figure 2. Foamed concrete ingredients

Table 1. Summary of binders used in foamed concrete

Replaced material	Additives	Cement: binder	Physical properties			Mechanical properties (28 days)		Reference
			Density [kg/m^3]	Shrinkage [%]	Porosity/ Sorptivity [%, mm]	Compression Strength [MPa]	Flexural Strength [MPa]	
Cement	FA-class F	1 : 3		0.37	2.5 mm	5.5		(Narayanan, Ramamurthy, 2000)
	FA-class F	1 : 1	650 1000 1150	34 31 29		4 9 19		(Gelim, 2011)
	FA	1 : 1.5	1000–1200 1300–1500	0.06–0.10	<10	3.7–6.7 10–18.8		(Hilal, Thom, Dawson, 2015)
	BFS	Replacement 30–70 %	1300			2.2–0.5	6.1–2.2	(Roslan, Awang, Mydin, 2013)
Aggregate/ Filler	POFA	Replacement of Sand 10 to 20%	1000			3.28–5.22	1.36–1.8	(Lim, Tan, Lim, Lee, 2013)
	CB	Replacement 0-100% with 25% interval	750–550		65–72	3.0–1.9		(Aliabdo, Hassan, 2014)
	Laterite	Replacement of Sand 0-15% with 5% interval	800–1800			40–5		(Khaw, 2010)

Annotation: FA: Fly ash, SF: Silica fume, BFS: Blast furnace slag, POFA: Palm oil fuel ash, CB: Clay bricks

2.4 Water

The demand of water during preparation of aerated concrete is dependent on various factors: composition of binder material, type and loading of filler, and desired workability. The minimum percentage of water produces a harsh mix with breaking of bubbles, while a maximal water content produces a thin mixture with segregation of the materials. As per the recommendation made in ACI Committee 213, the water utilized on preparing a concrete mix must be clean and fresh.

2.5 Fibers

The use of polypropylene (PP) fibers in foamed concrete significantly improves its mechanical properties (Ollo, & Hays, 1998). According to Poznyak, and Melnyk (2014), using PP fibers it is possible to produce foam concrete with density of 650 kg/m^3, with compression strength up to 2.7 N/mm^2 and 76.4% of voids of sizes 0.2-1.0 mm. Due to their heavy weight, the use of steel fibers in foamed concrete is not suggested in literature.

3. Cellular Concrete Production Techniques

The production of foam concrete involves two alternative techniques: pre-foaming or mixed-foaming. In case of pre-foaming technique, the base mix (C+S+W) and aqueous foam are produced separately, and then the foam is thoroughly mixed into the prepared base mix. The mixed-foaming method has the foam agent blended along with the base mix (C+S+W) ingredients, and during the mixing process foam is produced resulting pores in the concrete structure. Figure 3 has a flowchart of production techniques of foamed concrete.

4. Mix Design Methods

The changes in the cement quantity and/or w/c ratio significantly affect strength and stiffness of the foamed concrete at a constant density. Increased density has an adverse effect on strength, stiffness, thermal insulation and water absorption capacity. Thus, proportions in the design of mix must be selected depending on practical requirements, such as strength, stiffness, shrinkage and, thermal insulation (Deijk, 1991). The design of mix proportions is done with the help of trial mixes, varying parameters such as s/c ratio, w/c ratio, and target density of the mixture (Taylor, 1965; Valore, 1954). At present, there is no proper guidance or relevant techniques available for designing the mix proportions of foam concrete. From prior literature, Table 2 summarizes various mix design methods that are adopted for the manufacturing of foamed concrete.

5. Typical Properties of Cellular Concrete

The cellular concrete properties are categorized as fresh, physical, functional and mechanical properties, shown in Table 3. The properties in fresh state include the mixture consistency, flowability, and stability, while dense state has physical, functional and mechanical properties.

5.1 Fresh state properties

The rheological properties of cellular concrete include flowability and self-compacting behavior (Jones, & McCarthy, 2005). The fresh properties are significantly affected by the (w/c) ratio, new raw materials, aggregates, type and percentage of foaming agent, used plasticizers, etc. (Brady, Jones, & Watts, 2001).

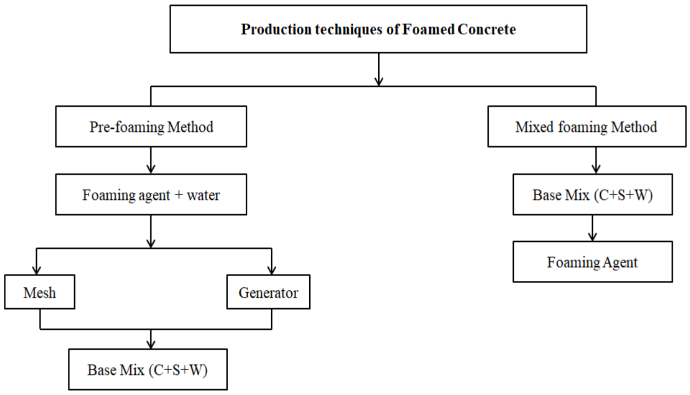

Figure 3. Flowchart of foamed concrete production

Table 2. Foamed concrete mix design methods from prior literature

Classification	Authors	Main features
Empirical method	(Kearsley, Mostert, 2005)	To find the coefficients of cement content (X) & foam content (V_f) which gives target casting density.
Absolute volume method	(Hilal, Ameer, 2015)	Selection of the concrete unit weight, cement quantity and, w/c ratio with FA and SF
Rational proportion method	(Zulkarnain, Ramli, 2011)	(C:S:W) = (1:1.5:0.45) with PA-1 as foaming agent and SF as admixture
Trial and error method	(Mydin, Wang, 2011)	Assumed proportion (Cement: Sand) = (2:1) with w/c ratio=0.5
	(Kishore, 2001)	Assumed proportions (Cement: Sand) = (1:1.5), (1:2) with constant w/c ratio=0.5

Annotations: FA: Fly ash, SF: Silica fume, PA-1: Protein agent-1

Table 3. Summary of cellular concrete properties

Reference	Physical Properties			Functional Properties			Mechanical Properties		
	Shrinkage	Porosity	Sorptivity	Fire resistance	Acoustic insulation	Thermal insulation	Young's modulus	Compression strength	Splitting tensile strength
(Valore, 1954)	Y	Y	Y	Y	Y	Y	Y	Y	Y
(Bing, Zhen, Ning, 2012)	Y				Y	Y	Y	Y	Y
(Brady, Jones, Watts, 2001)	Y					Y	Y	Y	
(Kearsley, & Wainwright, 2001)		Y	Y				Y	Y	Y
(Nambiar, Ramamurthy, 2008)	Y	Y	Y	Y	Y	Y		Y	Y
(Kishore, 2001)	Y			Y		Y		Y	
(Tan, Chen, Wang, Yang, Qi, Ma, Wang, Ma, 2017)							Y	Y	Y
(Kearsley, Wainwright, 2002)		Y						Y	
(Awang, Aljoumaily, & Noordin, 2014)	Y	Y				Y	Y	Y	

Annotation: Y indicates properties have been investigated.

5.2 Physical properties

5.2.1 Density

The fresh density estimates the exact quantity of ingredients required for the mix design and achieves control during casting of specimen. The dry density maintains physical and engineering properties of rigid foamed concrete.

5.2.2 Shrinkage

The shrinkage is a drawback of foamed concrete, which was observed on cast specimens after 3 weeks (McGovern, 2000). The hardened matrix has shrinkage in the range 0.1-0.35 % of the total volume of concrete (Roslan, Awang, Azree, & Mydin, 2011).

5.2.3 Porosity

The porosity becomes crucial as it adversely affects various engineering and durability properties. The porosity of hardened foamed concrete in turn is affected by various factors like the mix design proportions, foaming agents, and type of curing. A high water/cement ratio induces porosity that significantly influences performance of the concrete (Kearsley, & Wainwright, 2001).

5.2.4 Capillarity (Sorptivity)

The sorptivity influences the durability properties, and mostly depends on the concrete density, type and percentage of foaming agent, plasticizers and admixtures, permeability, and type of curing (Ramamurthy, & Nambiar, 2009). A suitable range of sorptivity for a light-weight material is 4-8 % as recommended by ACI 213R.

5.3 Functional properties

5.3.1 Fire resistance

The fire resistance depends on the proportions of the mixed ingredients in the foamed concrete (Sach, & Seifert, 1999). Generally, decreased density of the cellular concrete improves its performance during fire attack. The literature study indicates that foamed concrete in the density range from 950 to1200 kg/m^3 will resist fire for up to 2-3.5 hours.

5.3.2 Acoustic insulation

The foamed concrete achieves better acoustic insulation than conventional concrete because of its cellular structure. The sound insulation is mostly based on the concrete matrix rigidity (Deijk, 1991; Narayanan & Ramamurthy, 2000). The cellular walls in cellular concrete transfer sound for up to 3% relative to the wall made with conventional concrete (Valore, 1954). The cellular concrete has sound absorption potential 10 times greater than the dense concrete.

5.4 Mechanical properties

5.4.1 Compression strength

The significant reduction in concrete density influences its compression strength. The strength of concrete in compression is mainly dependent on different aspects such as w/b ratio, characteristics of foaming agent, type of sand particles, curing conditions, c/s ratio, and characteristics of added ingredients (Deijk, 1991; Valore, 1954). The compressive strength of foam concrete at the age of 28 days is from 43 to 0.6 N/mm^2 with plastic density range from 1800 to 280 kg/m^3, respectively (Cox, & Dijk, 2002). According to Nambiar, and Ramamurthy (2006), an excessive dose of foaming agent results in decreased compression strength of the foam concrete, because of excessive formation of air voids and reduced density. Many studies have been carried out on the compressive strength of foam concrete considering different fillers/additives, admixtures, foaming agents, and fibers, along with parameters such as density, water content, elevated temperature etc. Also, the foam concrete strength is dependent on different pozzolonic materials, cement content, mix proportions, w/b ratio, curing method etc. (Huiskes, Keulen, Yu, & Brouwers, 2006). The values of compression strength of foam concrete for the densities 500, 700, 800 and 1000 kg/m^3 were 5.90 ± 0.2, 5.10 ± 0.2, 3.80 ± 0.3 and 1.40 ± 0.2 MPa, respectively (Marta, Alfred, & Marcin, 2020). The strength in compression decreases with temperature for all densities (Mydin, & Wang, 2011). Table 4 illustrates the prediction models for compressive strength of foamed concrete.

5.4.2 Splitting tensile strength

For foamed concrete, the ratio of split-tensile/compressive strength lies in 0.2-0.4, which is greater in comparison with conventional concrete that attains the range 0.08-0.11 (Byun, Song, & Song, 1998). The tensile strength of foamed concrete has been increased nearly 32% by adding polypropylene (PP) fibers, relative concrete without PP fibers (Bing, Zhen, & Ning, 2012). Table 5 illustrates the empirical models estimating split tensile strength of foamed concrete.

Table 4. Empirical relations of compressive strength for foam concrete

Equations	Annotations	Reference
$Fc = Ks \ln[\frac{Pcr}{P}]$	P_{cr} = Critical porosity to null strength	(Robler, M. & Odler I.,1985)
$Fc = Po\ (1-P)^{n}$	*Po*= Zero porosity, n= Balshin's constant	(Narayanan, N. 1999)

Table 5. Empirical relations of split tensile strength for foam concrete

Equations	Annotations	Reference
$Ft = 0.20\ (Fc)^{0.70}$	F_c = 28 days compressive strength, for density range 1400-1800 kg/m^3	(Oluokun, F. 1991)
$Ft = 0.23(Fc)^{0.67}$	F_c = 28 days compressive strength	(C.E.B.F.I.P. 1993)
$Ft = 0.23(Fc)^{0.67}$	F_c = compressive strength for concrete with lightweight aggregate	(C.F.M. Code 1990)

5.4.3 Flexural strength

The foamed concrete possesses a ratio of flexural to compression strength in the range 25-35% (Valore, 1954). The flexural strength at 28 days increases with addition of Nano-GGBS and Nano-RHA in LDFC as a replacement to cement by 2.87%, 3.62%, 3.82% and 5.03%, 2.29%, 7.42% with different densities ±800, ±1000 and ±1300 kg/m^3 respectively. Generally, the development of flexural strength is linearly related with compressive strength (Tambe, & Nemade, 2022).

5.4.4 Young's modulus

The Young's modulus is a measure of stress–strain relationship, which plays an important role to the contours of deformation under working loads (Tambe & Nemade, 2021). Foam concrete with dry densities in 500-1600 kg/m^3 has modulus of elasticity within the range 1.0-12 KN/m^2 (Brady, Jones & Watts, 2001). The Young's modulus of cellular concrete is four times smaller than that of conventional concrete (Jones & McCarthy, 2005). Table 6 illustrates empirical models for estimating the Young's modulus of foamed concrete.

6. Foamed Concrete Applications

The foamed concrete has a wide range of applications in civil engineering because of its distinct properties including reduced density, good flowability, self-compacting behavior, low thermal conductivity, and economy (Nambiar, K. Ramamurthy, 2009). Also, cellular concrete has been extensively used in manufacturing prefabricated wall panels and beams, corrugated panels, pavement sub-base, trench filling, soil compaction, and in geotechnical engineering (Figure 4). Cellular concrete is widely used especially in regions facing problems with shortage of houses, adverse weather conditions, hurricanes, and earthquakes (Mindess, 2014). Foamed concrete plays an important role in earthquake-prone regions, in structures as well as water storage reservoirs, which need continuous retrofitting after seismic activity (Nambiar & Ramamurthy, 2009). Foamed concrete is in widespread use for grouting of tunnels, flowable fills, and in ground improvement applications (Mindess, 2014; Weigler & Karl, 1980).

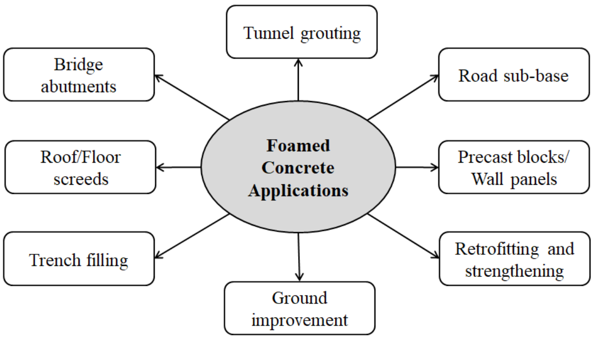

Figure 4. Foamed concrete application

7. Conclusions

The findings of this study indicate that the lack of a precise method for designing the mix of foamed concrete significantly affects the outcomes of cellular concrete. To maintain significant stability and consistency of foam concrete, it is recommended that cement should be partially replaced with supplementary pozzolanic materials along with using lightweight aggregates, and the proportion of foaming agent should be reduced.

The targeted casting density and expected strength significantly depend on the w/b ratio, characteristics of foam agent, distribution of voids, mix proportions, and foamed concrete production technique.

The shrinkage and capillarity of cellular concrete in its dense state are in the ranges of 10-35% by volume of concrete and 4-8%, respectively, for lightweight materials. The fire resistance of the concrete matrix decreases with density. The foam concrete possesses excellent performance in sound insulation, about 10-fold better than normal concrete. The mechanical strength mainly depends on shape, size, and mechanism forming the voids, age of the specimen, pattern of loading, characteristics of ingredients, and conditions of curing. The ratio of split-tensile/compressive strengths lies within 0.2-0.4, and is greater than that of conventional concrete within 0.08-0.11. The foamed concrete possesses a ratio of flexural to compression strengths in the range of 25-35%. The Young's modulus of cellular concrete is four times smaller than that of conventional concrete.

According to this literature survey, the identified gaps for future studies are: (1) to develop more precise models for determining mix proportions of foam concrete with code provisions; (2) the long term performance of fiber reinforced foamed concrete should be investigated in fresh and hardened state; (3) the problems associated with mixing, transporting, pumping and finishing should be solved in the context of industrial production of foamed concrete; and (4) to produce sustainably foamed concrete by integrating industrial and agricultural residual wastes for cement replacement at optimum percentages.

Table 6. Empirical relations of Young's modulus for foam concrete

Equations	Annotations	Reference
$E = 5.31\, x\, (W - 853)$	for density range 200-800 kg/m^3	(Tada, 1986)
$E = 0.42 Fc^{1.18}$	F_c = 28 days compressive strength, sand as fine aggregate	(Jones, & McCarthy, 2005)
$E = 33(W)^{1.5}\sqrt{Fc}$	F_c = compressive strength for concrete, W= density of concrete	(McCormick, 1967)

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