Thermal Properties of Foamed Concrete: A Review

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Abstract Among various types of building insulation materials developed to solve the problem of energy crisis, foam concrete is particularly interesting for its special attributes such as excellent low density, high flowability and excellent thermal insulation. The focus of this paper is to classify the literature on thermal behaviour of foamed concrete which includes the major factors affecting thermal properties and available methods of measuring it along with its pros and cons. Based on the review conducted it is observed that among the various factors studied, the microstructural parameters such as porosity, pore size and pore shape influences the thermal conductivity of foamed concrete to a great extent. Further, the literature evidence indicates that the constituent materials affects the microstructure of foamed concrete, which eventually affects its thermal behaviour. Also, studies indicate that use of foamed concrete for different structural and non-structural building applications is a viable method for reducing the heat transfer owning to its lower thermal conductivity value.

Keywords Foamed concrete · Thermal conductivity · Thermal insulation · Low density · Thermal diffusivity

1 Introduction

Considering the tremendous population boom in the recent decades and limited sources of natural energy, energy conservation becomes a prima facie solution that needs to be addressed. As per report of united nations environment program (UNEP)

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published in 2009, about one-third of the total energy consumption and 30% of greenhouse gas emissions are attributed to construction sector in most countries [1]. Since most people spend 90% of time living indoor for which 40% of the energy is consumed to overcome the heat flow and acquisition via surface coating and building wall units, hence prioritizing energy conservation over thermal comfort becomes rather a debatable issue [2, 3]. Using materials with low thermal conductivity (TC) during design and construction of building will help to reduce this energy consumption to a great extent. Foamed concrete which is classified as lightweight concrete (Density 400–1850 kg/m^3) can be considered as one of the most suitable material in modern building industry from thermal insulation point of view. It is basically a cement paste or mortar with air voids entrained by suitable foaming agent and possess special attributes such as low self-weight, high flowability, minimal consumption of aggregates, and excellent thermal insulation properties [4, 5]. Foamed concrete can be prepared by two techniques, pre-foaming method where a stabilized foam is prepared separately with the help of air compressor and then later mixed with base mix (consisting of cement, sand and water) while in other, mix foaming method, foam agent solution is practically mixed along with base mix in an high speed mixer [4, 6]. Air being poorest conductor of heat, light weight foamed concrete (LFC) which signifies greater porosity due to air entrainment possess lower thermal conductivity which varies according to the degree of porosity. Although the material was first patented in 1923 [7], its application in construction as lightweight non- and semi-structural material have increased in the last few years. Because of its wide spread use in countries like Netherlands, Sweden, Germany, USA, Switzerland and UK, investigators have been considering its engineering properties [8–10]. From the first comprehensive review on cellular concrete presented by Valore in 1954, there have been several reviews focusing on its applications and properties, but a detailed review on thermal properties of foamed concrete is still not available [7, 11–13]. Hence the objective of this paper is to present a state of art review of the available literature on thermal properties of foamed concrete, which includes the major factors influencing the thermal properties. The available literature on thermal properties of foamed concrete being limited, at some instances thermal performance of other types of lightweight concrete and normal weight concrete is also discussed for comparative analysis.

Thermal conductivity, thermal diffusivity and specific heat are considered as thermo-physical properties of foamed concrete. Thermal diffusivity (α-value) expresses the rate of heat spread through materials while specific heat (C-value) represents the heat storage capability of material [14]. The thermal conductivity (k-value) which refers to heat transfer by conduction through material is considered as most important property of all [15]. Though there are various steady state and transient methods that are used to measure the thermal conductivity of materials but it was observed that different methods implemented for the same specimens may result in different values of thermal conductivity [16, 17]. For calculating the energy consumption of buildings it is deemed necessary to have accurate values of thermal conductivity, however insufficient literature on suitable measurement methods compels to have a more systematic research in this direction. Hence, this paper also reviews pros and cons of various measurement methods for the thermal conductivity of foamed concrete.

2 Thermal Conductivity Measurement Methods for Foamed Concrete

Out of all the thermos-physical properties of foamed concrete, thermal conductivity (k-Value) is commonly used to check the energy performance of buildings and for conducting energy audits of the existing buildings [18, 19]. Considering this most of the researchers tried to address factors affecting Thermal conductivity (TC). TC which demonstrates heat conduction capability of material is measured primarily by two approaches namely steady state methods and transient methods which have different heat transfer conditions across materials [20–22]. A constant heat transfer approach is adopted by steady state methods, where in the temperature or heat flow is not dependent on time while transient method is dependent on time and temperature changes over time. A graphical representation of different available TC measurement methods of foamed concrete is shown in Fig. 1, while Table 1 summarizes the different TC measurement techniques, specimen sizes, testing ages, dry density range, corresponding TC range and scientific standard reported by researchers in previous studies. Also based on literature review the percentage distribution of usage of different TC measurement methods employed for foamed concrete over 32 studies is shown in Fig. 2.

2.1 *Steady State Method*

In steady state method the thermal conductivity is measured in just one Cartesian direction. From Table 1 it can be noted that the sample size required for instruments based on steady state method is much larger than instruments based on transient

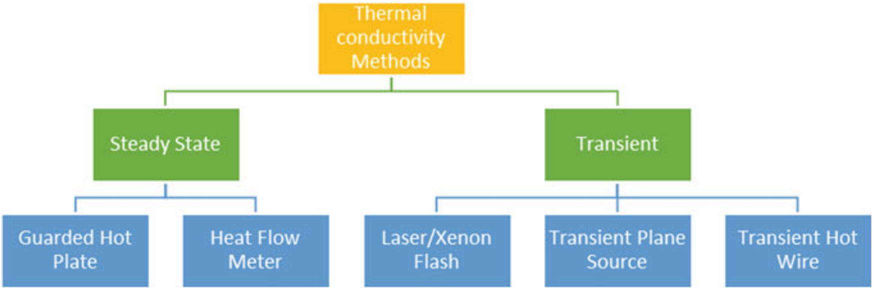

Fig. 1 Different thermal conductivity measurement methods

Table 1 Summary of thermal conductivity measurement techniques

	Measurement technique	Description	Specimen size (mm)	Testing age (days)	Standards reported by researchers	Dry density (kg/m^3)	T.C range measured (W/mK)	Refs.
Steady state method	GHP	Effect of porosity, density and pore size on K-value of FC	300 × 300 × 50	14	ASTM C 177	650–1200	0.23–0.39	[23]
	GHP	Effect of OPS as coarse aggregate on K-value	300 × 300 × 50	28	NA	1100–1600	0.4–0.57	[24]
	GHP	Effect of LS waste on K-value	300 × 300 × 50	28	IS 3346	800–1000	0.3–0.33	[17]
	GHP	Effect of SF, slag and FA on K-value	NA	NA	ASTM C 177	1490–430	0.72–0.16	[25]
	GHP	Effect of OPS on K-value of GFC	300 × 300 × 55	28	BS EN 12664	1300–1700	0.47–0.54	[26]
	GHP	Effect of temperature on K-value of FC	430 × 415 × 150	NA	ASTM C 177	650–1850	0.226–0.484	[27]
	GHP	Effect of pore size on the K-value of FC	300 × 300 × 30	28	NA	252–1870	0.065–0.5	[28]
	GHP	Effect of newspaper sandwiched on K-value of FC	300 × 300 × 50	28	BS EN 12664	1100–1700	0621–0391	[29]
	GHP	Effect of POFA on	300 × 300 × 100	28	BS EN 12664	1300±50	0.65–0.74	[30]
	GHP	Effect of W/C ratio and HPMC on K-value	300 × 300 × 30	NA	GB/T 10294	181–409	0.059–0.078	[31]
						151–180	0.050–0.055	

(continued)

Table 1 (continued)

	Measurement technique	Description	Specimen size (mm)	Testing age (days)	Standards reported by researchers	Dry density (kg/m^3)	T.C range measured (W/mK)	Refs.
	HFM	K-value for super low density FC	300 × 300 × 30	28	ASTM C 518	150–300	0.050–0.071	[32]
	HFM	K-value for very low density FC	300 × 300 × 30	28	GB/T 10294-2008	110–270	0.036–0.063	[33]
	HFM	Effect of FA and SF replacement on K-value	305 × 305 × 50	28	ISO 8301:1996	1280–1870	0.475–0.962	[34]
	HFM	Effect of MPC as binder and hydrogen peroxide as foaming agent on K-value	300 × 300 × 30	28	ASTM C518	300–1000	0.08–0.23	[35]
Transient Method	TPS	Effects of foamed content, QL and SF on the K-value of soil-based FC	200 × 200 × 50	28	NA	800–1800	0.19–0.755	[36]
	TPS	Effect of LS waste on K-value	30 × 30 × 20	28	NA	800–1000	0.32–0.34	[17]
	TPS	Effect of Fine aggregate proportion on K-value of FC	70 × 70 × 70	60	NA	916–1070	0.132–0.230	[37]
	TPS	Effect of varying FA % on K-value	25 × 50 × 10	NA	NA	600–1400	0.19–0.59	[38, 39]

(continued)

Table 1 (continued)

	Measurement technique	Description	Specimen size (mm)	Testing age (days)	Standards reported by researchers	Dry density (kg/m^3)	T.C range measured (W/mK)	Refs.
	TPS	Effect of Mineral additives—PFA, POFA, SF, WA Fibres—Steel, Polypropylene, coconut on K-value	Ø 75 mm × 40 mm	NA	NA	700–1400	0.24–0.74	[40]
	TPS	Effect of alkali activated class C FA on K-value	Ø 50 mm × 100 mm	28	ISO 22007–2	940–1310	0.23–0.31	[41]
	TPS	Effect of EPS beads on K-value of FC	200 × 200 × 50	NA	NA	400–800	0.07–0.15	[42]
	TPS	Effect of aero gel on K-value of ultra-lightweight FC	NA	NA	NA	700–200	0.164–0.049	[43]
	TPS	Effect of slag substitution on K-value of GFC.	Ø 53 mm × 15 mm	28	NA	585–1370	0.15–.048	[44]
	THW	Effect of water repellents on K-value	NA	28	NA	550	0.149–0.159	[45]
	THW	Effect of geopolymerisation on K- value	Ø 50 mm × 110 mm	56	NA	978	0.28	[46]
	THW	Effect of FA, SF and foamed % on K-value	40 × 40 × 160	NA	EN 993-15	873–1998	0.2385–0.942	[47]

FC Foamed concrete, *OPS* Oil palm shells, *LS* Limestone slurry, *FA* Flyash, *SF* Silica fume, *QL* Quick lime, *GFC* Geopolymer foamed concrete, *POFA* Palm oil fuel ash, *HPMC* Hydroxypropyl methyl cellulose, *MPC* Magnesium phosphate cement, *PFA* Pulverized fly ash, *WA* Wood ash, *EPS* Expanded polystyrene, *TC* Thermal conductivity (k-value), *NA* Not available in literature

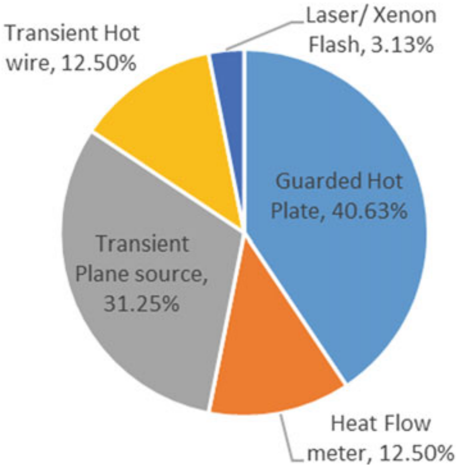

Fig. 2 The distribution of usage of different TC measurement methods employed for foamed concrete

method [17]. In contrast to transient methods, it is possible to determine the overall thermal conductivity of multi-layered specimens by using steady state method [29]. Though, the time taken by the steady state method is more but the k-value measured is more precise than that of transient method.

Guarded Hot Plate Method (GHP) The TC of a foamed concrete can be measured using GHP method by placing the specimen in between two plates cold and hot as mentioned in ASTM C177 [48]. In most of the cases the temperature of cold and hot plate were set as 18 and 40 °C to represent the interior and exterior of building structure respectively [24, 26, 30]. In case of GHP method the major advantage is its sophisticated nature and straight forward evaluation of results However long run time which is around 3 h can be considered as disadvantage [28]. Usually the specimens that were used for testing with GHP method were oven dried at above 100 °C for 24 h [26, 30, 31].

Heat Flow Meter (HFM) The HFM is an axial type steady state instrument based on measurement of density of heat flow rate. The test is conducted by placing the specimen in between the heat source at top and the sink at the bottom with the heat-flow transducer (flux gauge) placed between sample and sink. The merits and demerits of HFM are similar to that of guarded hot plate. Researchers have used this method for determining the TC of very low density foamed concrete as this method gives more accurate results at very low TC values [32, 33].

2.2 *Transient Method*

As compared to steady state method for which four different functional units (heat sink, heat source, thermometer, and sample) are required, the transient method requires only two (heat source and sample). Here the heat source also acts as thermometer while the specimen samples act as heat sink. TC of heterogeneous materials with high moisture content can be calculated by using transient method, though repetitive trials are required for precise results [49, 50]. The transient instruments come in two different classes namely contact and non-contact. Transient plane source and transient hot wire comes in contact class where there needs to be contact between sensor and specimen, while the non-contact class consists of the optical laser/xenon flash techniques.

Transient Plane Source (TPS) Which comes under contact class can be used to measure TC as well as thermal diffusivity and specific heat of foamed concrete [38–41, 44]. The hot disk sensor measuring the current and voltage drop over a period of time is embedded in between the two halves of the specimens forms a key part of the TPS technique [51]. The main advantages of this method are flexible specimen size and very less testing time which is in range of few seconds [17, 36, 41–43]. Since it comes in contact class, for better and precise results and minimizing the influence of contact resistance, the surfaces of the foamed concrete specimens need to be polished beforehand [36, 42, 44].

Transient Hot Wire (THW) is another contact class technique is method, which is usually used for measuring the TC of liquids but can also be used for solids. For measuring TC of solids two wires are required namely heater wire and a temperature sensor wire which normally have different functions.

Laser/Xenon Flash (LFA/XFA) Which is a non-contact class technique, is the most commonly used technique for determining the thermal diffusivity (directly) and TC (indirectly) of foamed concrete. While the major advantage of this method can be attributed to its ability of working over a broad temperature range and its simplicity in handling, however the requirement of a very small and homogeneous sample can be considered as disadvantage [3].

3 Factors Affecting Thermal Properties of Foamed Concrete

Table 2 summarizes the literature addressing various factors influencing the thermal properties of foamed concrete. Also it should be noted that, most researchers have investigated the TC rather than focusing on all thermal properties for foamed concrete as represented in Fig. 3 and observed in Table 2. The proportion of 39 studies evaluating the different thermal properties of foamed concrete are presented in Fig. 3. The subsequent section reviews the influence of various factors related to materials, mix composition and microstructure on thermal properties of foamed concrete.

Table 2 Factors affecting the Thermal conductivity

Factor	Type of additive	Foaming agent used	Observation	Density (kg/m^3)	Thermal properties	Other properties studied	Refs.
Air void system and density	None	Noraite PA-1 (protein based)	Lower density FC indicates greater porosity and hence lower TC.	650–1200	k = 0.23–0.39	Porosity and pore size	[23]
	Ultrafine GGBS and PF	Hydrogen peroxide	TC achieved was significantly lower than that of normal weight concrete (1.7 W/mK)	150–300	k = 0.05–0.07	CS, water absorption	[32]
	Foam replaced with EPS	Protein based	Increase in EPS % not only increased the strength but also decreased the T.C	400–800	k = 0.07–0.15	Porosity CS, TS	[42]
	None	NA	Super low density concrete with porosity ranging from 88–95% was achieved with extremely lower TC values	110–270	k = 0.036–0.063	Rheological tests, porosity, CS	[33]

(continued)

Table 2 (continued)

Factor	Type of additive	Foaming agent used	Observation	Density (kg/m^3)	Thermal properties	Other properties studied	Refs.
	None	Protein based	In case of high porosity FC radiation heat transfer is a considerable factor affecting TC. However the radiation influence starts diminishing as the porosity decreases.	252–1870	k = 0.065–0.5	Microstructure study, porosity	[28]
Moisture content and temperature	None	Noraite PA-1 (protein based)	The TC values of FC were less for high temperatures due to lower moisture content	650–1850	k = 0.226–0.484	Moisture content, Fire resistance.	[27]
	S.F as cement and F.A as filler replacement	EABASSOC (chemical)	T.C of prepared FC was more in saturated state compared to specimens in dry state due to presence of moisture.	1280–1870	k = 0.475–0.962	CS, TS	[34]
	GGBS	Synthetic	FC specimen with air dried curing showed the best thermal performance.	1167–1293	K = 0.62–0.72	CT, Ultrasonic pulse velocity	[52]

(continued)

Table 2 (continued)

Factor	Type of additive	Foaming agent used	Observation	Density (kg/m^3)	Thermal properties	Other properties studied	Refs.
Aggregate/ Filler Substitution	RTC	NA	Addition of RTC made concrete more thermal resistive due to improvement in porosity.	600 ± 25	k = 0.15–0.2	Porosity, Acoustic. Water absorption and CS	[53]
	OPS	Naphthalene sulfonated (Synthetic)	The T.C was on par with FC prepared with expanded perlite aggregate and very less compared to clay brick and blocks	1100–1600	k = 0.4–0.57	CS	[24]
	LS	Natural Protein based	T.C values were way less than normal brick and concrete	800–1000	k = 0.32–0.34 C = 1.025–1.07 α = 0.32–0.35	CS, Porosity	[17]
	OPS	Sika AER 50/50 (Synthetic)	The porous structure of OPS aggregates resulted in better thermal resistivity of OPS GFC compared to conventional materials	1300–1700	k = 0.47–0.54	Sorpitivity, porosity, CS TS and UPV	[26]

(continued)

Table 2 (continued)

Factor	Type of additive	Foaming agent used	Observation	Density (kg/m^3)	Thermal properties	Other properties studied	Refs.
	AP	NA	With the porosity maintained constant, the TC could be efficiently decreased by increasing the AP content and decreasing the cement content.	700–200	k = 0.164–0.049	CS, porosity	[43]
	POFA	Synthetic foaming agent	Replacement of sand with POFA as filler increased the TC due to densification of FC.	1300±50	k = 0.65–0.74	CS, TS	[30]
Binder/Cement and pozzolanic materials	PFA, POFA, SF, WA	Noraite PA-1 (protein based)	Use of S.F as mineral admixture resulted in less T.C than PFA. But when PFA mixed with optimum WA is used it exhibited better heat resistant behaviour.	700–1400	k = 0.24–0.74 C = 0.879–0.794 α = 0.39-0.69	None	[40]
	S.F and F.A	Hydrogen peroxide	TC of FC has much relevance with dry density	190–470	k = 0.05–0.085	CS	[54]
	FA, SF and slag	Protein based	TC depends mainly on porosity rather than mix constituents.	1490–430	k = 0.72–0.16	CS	[25]

(continued)

Table 2 (continued)

Factor	Type of additive	Foaming agent used	Observation	Density (kg/m^3)	Thermal properties	Other properties studied	Refs.
	FA, SF	Synthetic based	SF introduction resulted in superior compressive strength/TC ratios than FA introduction.	873–1998	k = 0.238–0.942	CS, water absorption, porosity	[47]
	MPC	Hydrogen peroxide	TC of the MPC foamed concrete is higher than that of OPC for a given dry density	300–1000	k = 0.08–0.23	Porosity, CS, water absorption	[35]
Mix Cement + Filler replacement	Soil as filler and SF and QL as cement replacement	Protein based	Addition of SF decreased TC while quick lime increased the T.C	800–1800	k = 0.19–0.755	Hygroscopic properties, CS,	[36]
	FA and lime as filler replacement, PF	Noraite PA-1 (protein based)	Addition of FA and PF decreased T.C	600–1400	k = 0.19–0.59 C = 0.54–0.98 α = 0.35–0.60	CS, flexural strength, porosity	[38, 39]
	S.F as cement and F.A as filler replacement	EABASSOC (chemical)	Addition of S.F and F.A leads to slightly increased TC in the dry state. However TC in the saturated state was slightly lower due to better microstructure	1280–1870	k = 0.475–0.962	CS, TS	[34]

(continued)

Table 2 (continued)

Factor	Type of additive	Foaming agent used	Observation	Density (kg/m^3)	Thermal properties	Other properties studied	Refs.
Influence of fibers and admixtures	Fibres- Steel, Polypropylene, coconut.	Noraite PA-1 (protein based)	Among various types of fibres studied coconut fibres showed lowest TC.	700–1400	k = 0.24–0.74	None.	[40]
					C = 0.879–0.794		
					α = 0.39–0.69		
	HPMC	Modified sodium alcohol ether sulfate	Addition of HPMC decreases TC to a great extent.	181–409	k = 0.059–0.078	Porosity	[31]
				151–180	k = 0.050–0.055		
	Newspaper	Synthetic	Addition of 0.05 g/cm^2 newspaper, sandwiched in foamed concrete panels were able to reduce the TC by 20%	1100–1700	k = 0.303–0.621	CS.	[29]

(continued)

Table 2 (continued)

Factor	Type of additive	Foaming agent used	Observation	Density (kg/m^3)	Thermal properties	Other properties studied	Refs.
	Water repellents	Protein based	The addition of potassium trimethylsilanolate (PT) and calcium stearate (CS) showed an increasing trend while siloxane-polymer (SP) showed irregular trend in case of TC	550	k = 0.149–0.159	CS, Sorpitivity and Hygroscopicity	[45]
Geopolymer Foam concrete	GGBS, FA	Protein based	Type of activator used in GFC does not affect the TC,	325–492	k = 0.088–0.129	Porosity, CS	[55]
	FA	Protein based	TC performance of alkali activated system was comparable with normal OPC foamed concrete system	940–1310	k = 0.23–0.31 C = 1.18–1.69 α = 0.18–0.20	None.	[41]
	Class F-FA, GGBS	NA	GFC exhibits better thermal insulation property than normal FC with similar density range.	585–1370	k = 0.15-.048 α = 0.27–0.34	CS, acoustic	[44]

K—Thermal conductivity (W/mK), C—Specific heat (J/g K), α—Thermal diffusivity (mm^2/s)
FC Foamed concrete, *OPS* Oil palm shells, *LS* Limestone slurry, *FA* Flyash, *SF* Silica fume, *QL* Quick lime, *GFC* Geopolymer foamed concrete, *POFA* Palm oil fuel ash, *HPMC* Hydroxypropyl methyl cellulose, *MPC* Magnesium phosphate cement, *PFA* Pulverized fly ash, *WA* Wood ash, *EPS* Expanded polystyrene, *PF* Polypropylene fibre, *RTC* Recycled tyre crumb, *AP* Aerogel powder, *CS* Compressive strength, *TS* Tensile strength

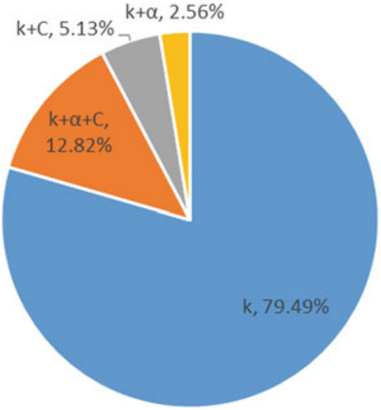

Fig. 3 Distribution of reported different thermal properties of foamed concrete (k—Thermal conductivity, C—Specific heat, α—Thermal diffusivity

3.1 Influence of Air Void System and Density

One of the most substantial factors influencing thermal properties is the density and subsequently porosity. Many of the earlier studies have established the correlation that thermal resistance is indirectly proportional to density of foamed concrete [23, 56, 57]. In this line, Pan et al. [32] prepared a super low density foamed concrete with density in range of 150–300 kg/m^3 and hence was able to achieve a very low TC of 0.05–0.07 W/mK. This was possible due to use of rapid hardening cement and accelerators which prevented the foam collapse by quick setting. Similar research was carried out by Jiang et al. [33] on very low density foamed concrete. Adding to above Chen and Liu [42] in their research replaced foam with EPS (expanded polystyrene) beads in foamed concrete. It was observed that there was a significant increase in T.C as well as compressive strength of concrete, though the density of the mixes remained almost similar. Hence the above finding proved that apart from density, properties of mix constituents also plays an important role in T.C of foamed concrete. Wei et al. [28] explored the effect of porosity level on thermal properties and established that at high porosity levels radiation heat transfer becomes a considerable factor while with decrease in porosity the radiation influence starts to diminish. TC is also predominantly influenced by directional homogeneity of pore distribution. Pores when arranged perpendicular to heat flow allowed more heat to pass through thus improving thermal resistance. However layer of pores were populated in parallel to heat flow direction offered lower thermal resistance [58].

3.2 *Influence of Moisture Content, Temperature and Curing Condition*

Studies on influence of moisture content on TC of foamed concrete proved that TC increases with increase in moisture content [11]. For instance every 1% increment in moisture content lead to increase in TC value by 6% [34]. This can be ascribed to the fact that TC of water is 25 times higher than that of air [59]. While investigating the influence of temperature variation on thermal properties of foamed concrete, Richard et al. [60] noted that rate of increase in TC with increase in density is lesser at lower temperature. Hence the thermal insulation property of foamed concrete was improved with reduction in temperature. On similar lines Othuman and Wang [27] investigated the thermal properties of foamed concrete at different temperatures ranging from 20 to 250 °C. Their experimental outcomes indicated that the TC remained constant with gradual increase in temperature till 90 °C after which it started to decrease rapidly till 170 °C. This can be attributed to evaporation of the available moisture in the pores of specimen. Beyond 170 °C the increase in temperature resulted in gradual increase in TC due to the radiation in pores. Hence moisture content in pores of foamed concrete plays an important role in thermal properties. It was also noted that specific heat was very less sensitive to temperature changes as compared to TC.

While studying the influence of curing conditions on TC, Zhao et al. [52] subjected foamed concrete specimens to four different curing conditions namely 28-day air, 7-day water + 21-day air, 28-day natural weather and 7-day water + 21-day natural weather. The 28-day air cured foamed concrete exhibited the lowest TC. This was due the lowest amount of moisture present in 28-day air cured specimens where in curing temperature and humidity was kept constant at 30 °C and 65% respectively. Further Ji et al. [61] reported that foamed concrete specimens cured at higher temperature showed lower TC. This could be attributed to the increased porosity resulting from increase in curing temperature.

3.3 *Influence of Aggregate/Filler Substitution*

Since the coarse aggregate (CA) phase is mostly absent in the foamed concrete, the filler mainly consists of only fine aggregate (FA) and the replacement of which also affects the thermal properties to a great extent. Researchers have tried to incorporate different waste materials such as recycled tyre crumbs [53], waste limestone slurry [17], granulated blast furnace slag [62], palm oil fuel ash (POFA) [30] etc. as replacement for filler in foam concrete. Their experimental outcomes indicated that the thermal insulation properties were improved in most cases due to increase in porosity. However, use of POFA as filler replacement resulted in increase in TC due to densification of microstructure. Li et al. [43] were able to prepare a high performance aerogel foamed concrete by using aerogel powder of extreme low density as filler which resulted in dry density of 198 kg/m^3 and TC of 0.049 W/Mk with better compressive strength and decreased porosity. Salvini et al. [63] proposed that use of porous ceramics as filler material for preparation of foamed concrete could result in insulating refractory composite with an acceptable thermal conductivity.

Though natural coarse aggregate due to their high specific gravity and angular shape are not preferred in foamed concrete but experimental evidences have showed that in order to improve the properties of foamed concrete, researchers have used lightweight aggregate composed of expanded clays and expanded shales as CA providing a filler effect [57]. This not only resulted in better mechanical properties but also improved the thermal resistivity of foamed concrete. On similar lines oil palm shells (OPS) were used as CA for preparing foamed concrete. The physical and thermal properties were found to be on par with concrete prepared with expanded perlite aggregates as OPS itself are porous aggregates having large number of micropores [24, 26, 64]. Wang et al. [65] prepared a new type of foamed concrete with a density of 600 kg/m^3 by incorporating ceramsite as lightweight coarse aggregate which resulted in concrete with best thermal and mechanical behaviour.

3.4 Influence of Binder/Cement and Pozzolanic Materials

The chemistry of cement plays a significant role on the thermal performance of foamed concrete. To date very few research works have been undertaken on influence of type of binder on thermal properties of foamed concrete. Based on the extensive studies, researchers have established that higher heat of hydration of cement also have a significant role on thermal performance of foamed concrete [66, 67]. Hence the above problem can be addressed by optimum use of cement and its replacement with pozzolanic fly ash with lower heat of hydration. In a study by Li et al. [35] magnesium phosphate cement (MPC) was used instead of OPC and the prepared foamed concrete was found to have higher TC along with higher compressive strength for a given dry density.

Studies on use of flyash and silica fume as additive in foamed concrete showed slight increase in TC. However a significant increase in the mechanical properties was observed and this could be attributed to the densification of microstructure due to addition of additives [25, 47]. The above increment in TC was more significant for silica fume concrete when compared to flyash blended concrete. However the TC range reported for silica fume concrete was on par with similar density range of non-autoclaved cellular gas concrete produced with perlite [68]. Ganesan et al. [40] based on their comparative studies on the various possible binder replacements such as Pulverized fuel ash (PFA), Silica Fume (SF), Palm oil fuel ash (POFA) and Wood ash (WA), found out that replacement with combination of PFA and wood ash provided the best thermal performance of all.

3.5 *Influence of Cement + Filler Replacement*

In order to optimize the performance as well as cost of foamed concrete, researchers have tried to replace the cement as well as filler with various substitutes. Similar such attempt was made when silica fume (SF) was used as cement replacement and flyash (FA) as fine sand replacement [34]. This lead to better mechanical properties but a slight increase in TC was observed for oven dried specimens due to dense microstructure. On contrary, in case of saturated specimens the TC observed was lower and this could be attributed to reduced water absorption resulting from improved microstructure of SF-FA concrete. In same line, Cong and Bing [36] based on comparative studies on use of SF and quick lime as cement replacement with soil as filler in foamed concrete, proved that addition of quick lime resulted in poor thermal performance. This was because in mixes with quick lime foam collapse occurred due to consumption of water from foam surface by quick lime while mixing and eventually leading to increase in concrete density. Awang and Mydin [38, 39] replaced the filler with lime and cement with flyash and found out that lime as aggregate replacement did not contribute much on mechanical behaviour but good in thermal performance by improving all three thermo-physical properties.

3.6 *Influence of Addition of Fibers and Admixtures*

Generally, fibers and admixtures though added in small quantities leave a good impact on the properties of foamed concrete. Use of fibres in foamed concrete resulted in better thermal as well as shrinkage resistance performance. This was due to ability of fibres to form small and uniform pores by swelling and shrinking in a concrete during mixing and drying [38, 39]. Researchers have tried the incorporation of various synthetic fibers such as polypropylene (PP), alkaline resistance glass, kenaf, steel, basalt, chrysotile asbestos and also natural fibers like oil palm fiber, coir (coconut) fibres etc. in foamed concrete. Ganesan et al. [40] studied the relative performance of different fibres such as steel, PP and coir and their experimental outcomes proved that coir fibres showed the best performance of all. Based on a similar comparative study of fibres such as PP, alkaline resistance glass, kenaf, steel and oil palm fibre Ahmad and Awang [69] reported that PP fibres turned out to be better. On the same note, Li et al. [70] studied the seismic and thermal behaviour of foam concrete precast self-insulation shear wall panels with polypropylene fibres incorporated in the mix and reported that the TC was very much lesser than previous related research. On contrary another study on synthetic fibers showed that thermal performance of polypropylene was relatively poor than basalt and chrysotile asbestos fibre [71].

Experimental results presented by Ng and Low [29] showed that mere addition of 0.05 g/cm^2 newspaper, sandwiched in foamed concrete panels were able to reduce the TC by 20% for same density. Sang et al. [31] found that the mere inclusion of 4% of hydroxypropyl methyl cellulose (HPMC) in foamed concrete lead to decrease in TC to a great extent due to increase in porosity. Ma and Chen [45] used water repellents in foamed concrete and found out that the addition of potassium trimethylsilanolate (PT) and calcium stearate (CS) showed an increasing trend while siloxane-based polymer (SP) showed constant trend in case of thermal conductivity.

3.7 Geopolymer Foamed Concrete (GFC)

Yang et al. [55] studied the properties of alkali activated GGBS foamed concrete prepared with three different types of activators. Based on their studies it was concluded that TC of alkali activated GGBS foamed concrete was found to be more dependent on density rather than on type of activator used. Liu et al. [26] evaluated the thermal properties of geopolymer foamed concrete (GFC) in which crushed oil palm shells were used as coarse aggregates. The obtained results established that the foamed geopolymer concrete was superior in thermal resistivity compared to conventional blocks and bricks available in market. While investigating the thermal properties of GFC made from class F fly ash along with partial slag substitution researchers reported. better thermal insulation properties than normal Portland cement foamed concrete at the same density [41, 44]. This was due to the low proportion of chemically bound water in the geopolymer gel, providing a more discontinuous gel structure in these material. The thermal diffusivity and specific heat values were also on the lower side, thus recommending GFC as excellent thermal insulation building material. A commercially viable and environmentally-friendly geopolymer foamed concrete was synthesized with a mix composed of a hollow cenospheres exhibiting high strength/density ratio. The material thus prepared reported a strength of 17.5 MPa at density of 978 kg/m^3 with TC value to be around 0.28 W/mK which is comparable to normal foamed concrete [46].

4 Thermal Insulating Applications of Foamed Concrete

Properties of foamed concrete like low self-weight, low thermal conductivity, high flowability, self-compacting nature, ease of production etc., have made possible the use of foam concrete over a wide range of applications in structural as well as nonstructural areas [4, 72]. On reviewing the history of use of foamed concrete it was found that in the 1930s, the Soviet Union started extensive manufacturing of thermally insulating cellular concrete blocks, wall boards, and floor slab for commercial and residential structures. later in the mid-1940 and 1950s, equipment and standards were developed, some of which are still used today [73]. Due to superior thermal insulation property, foamed concrete was used for roof insulation in middle east and South Africa. In the middle far east, almost 3000 houses were built between 1948 and 1958 using 1100–1500 kg/m^3 density of foamed concrete [13, 19]. The conditions of these dwellings assessed later were found to have performed better than contemporary timber or brick and concrete houses. In India a successful trial has been attempted in Delhi by G. B. Singh, who had constructed a G + 3 storey building with foamed concrete [74]. Approximately 250,000 m^3 of foamed concrete is used annually in Korea as an essential component in floor heating system [55]. Hence based upon the above instances it is evident that foam concrete can be a promising thermally insulating building material.

5 Summary

Based on the review conducted, the salient observations pertaining to the thermal properties of foamed concrete are summarized below. In recent years, considering the importance of energy efficiency in building sector, researchers have prioritized studies on thermal properties of foamed concrete. Out of all three thermos-physical properties, it is observed 80% of researchers had studied thermal conductivity of foamed concrete.

Steady state or transient methods are the most commonly used methods for evaluating the thermal properties of foamed concrete. it should be noted that though transient method does not prove its greater accuracy over steady state methods, however very less experiment measurement time, ease of use, compactability, and the ability to measure TC of moist specimens can be considered as some factors compelling the researchers for preferring transient methods over steady state.

Review on factors affecting thermal properties of foamed concrete indicates that density and the air void system are the most substantial factors. Studies indicated that thermal resistance is indirectly proportional to density and directly proportional to porosity of foamed concrete. Moisture content, temperature and curing conditions also have a considerable impact on thermal properties of foamed concrete. Foamed concrete prepared with lightweight aggregates not only improves mechanical properties but also significantly improve the thermal resistivity of foamed concrete. Selection of type of filler also has significant influence on TC of foamed concrete as it modifies the microstructure of concrete to a great extent. Further selection of binder also alters the thermal performance as the heat of hydration is dependent on it. Fibres and admixtures though added in small quantities but affects the micro structure and porosity to a great extent in foamed concrete thus reducing the thermal conductivity. Geopolymer foamed concrete not only on par but in some cases resulted in better insulating properties than normal foamed concrete. Hence the above extensive review indicates that foamed concrete has great potential to improve the energy performance of buildings for structural as well as non-structural applications.

In summary, it appears that availability of literature on the thermal properties of foamed concrete is very limited when compared to normal weight concrete. Hence the review highlights the need for more systematic studies to evaluate the thermal behaviour of foamed concrete and energy consumption of buildings in different weather conditions.

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