Construction and Building Materials 220 (2019) 253–266

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Investigate the influence of expanded clay aggregate and silica fume on the properties of lightweight concrete

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HIGHLIGHTS

- Energy efficient concrete with environmental impact was produced.
- The expanded clay aggregate and foam was used to produce thermal mass concrete.
- Lightweight concrete exhibited higher indoor thermal comfort properties.
- Produced concrete provided the balance between thermal and structural performance.

ARTICLE INFO

Article history:
Received 29 December 2018
Received in revised form 14 May 2019
Accepted 28 May 2019
Available online 10 June 2019

Keywords:
Foamed concrete
Expanded clay aggregate
Porosity
Sorptivity
Thermal conductivity

ABSTRACT

This study concentrated on the formulation of self-flowing and an energy efficient lightweight aggregate foamed concrete (LAFC) to be employed as thermal insulation, thermal mass and structural material. Low density concrete mixtures (for the density values from 800 to 1300 kg/m^3) were prepared by changing the volume of lightweight expanded clay aggregate (ECA) from 49.4% to 20.1%. Flowing properties of concrete mixtures were improved with the help of stable foam. Ordinary Portland cement (OPC) was replaced by the 5% and 10% silica fume (SF) to examine the influence of SF on the properties of LAFC. Compressive strength and tensile strength of LAFC mixtures were respectively enhanced from 6.5 MPa to 24.30 MPa and 0.52 MPa to 1.63 MPa by reducing the volume of ECA from 49.4% to 20.1%. LAFC mixture (800-0SF) with the lowest density exhibited highest porosity and sorption coefficient value of 70.63% and 2.56 kg m^{-2} min$^{-0.5}$. Thermal conductivity, volumetric specific heat capacity and thermal diffusivity of LAFC mixtures were in the range of 0.23–0.45 W m^{-1} K^{-1}, 1136–1631 kJ/m^3.K and 0.20–0.275 mm^2/s respectively. SEM analysis revealed that reduction in the volume of ECA and addition of SF densified the microstructure of LAFC. Finally, LAFC mixtures were classified into Class-I, Class-II and Class-III grade concretes for the structure and insulation purposes as per functional classification of RILEM.

1. Introduction

Due to the scarcity of available energy resources, a lot of researches are being conducted on the usage of energy saving and energy efficient materials, and some countries have included the use of these materials in their fundamental policy to conserve the natural resources. In China, construction industry nearly consumes 35% of total energy [1]. In the modern day, construction industry is rapidly growing industry because of the peak demands of contemporary infrastructure. In such cases, environmental stability and energy efficiency of buildings can be increased through the improvement in thermal properties of construction materials.

A lot of previous studies have examined the workability, mechanical, thermal and hygroscopic properties of lightweight concrete containing foam and lightweight aggregate. Lightweight concretes, foamed concretes and aerated concretes with excellent thermal properties have been used as exterior wall materials [2–9]. Foamed concrete belongs to the family of lightweight concrete and it is mainly composed of Portland cement (OPC), foaming agent, and aggregate. The purpose of using foaming agent is to introduce entrapped air in lightweight concrete [10]. Generally, mechanical properties of Lightweight aggregate foamed concrete (LAFC) are inferior to normal weight concrete (NWC), but it can be employed as partition and load-bearing walls for the low-rise

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https://doi.org/10.1016/j.conbuildmat.2019.05.171
0950-0618/

buildings [5,11,12]. Opposite to normal weight concrete, Lightweight aggregate foamed concrete can be also used for thermal insulation, void filling, vibration attenuation and dead load reduction. Recently, foam concretes have been formulated with the wide range of densities (300–1600 kg/m^3), compressive strength (0.3–30 MPa) and thermal conductivities (0.2–0.8 Wm^{-1} K^{-1}) [4,6,13,14].

Lightweight aggregate concrete (LWAC) mainly improves the thermal and sound insulation properties of buildings beside its structural applications. Lightweight aggregate used in the LWAC should conforms to ASTM C330 [15] and 28 days compressive strength of LWAC should be at least 17 MPa with the density in the range of 1120–1920 kg/m^3 [16]. LWAC concrete can be prepared either by using naturally available lightweight aggregate or artificially made lightweight aggregate. Artificial LWA are normally produced by using the natural raw materials or byproducts [15]. Expanded clay aggregate (ECA) is a type of artificially produced LWA that is formed by expanding the natural clay at a high temperature of around 1200 °C in a rotary kiln [17–19]. The particles shape of ECA is spherical with they have a closed and barely porous outer surface as compared to inner structure that is black in the color and highly porous. Previously ECA has been used to prepare lightweight masonry plaster and mortar [20,21], self-healing concrete [22], structural lightweight and self-compacting concrete [7,12], as a filler in aluminum tubes [23], and for the thermal insulation purposes [7]. In the traditional concrete, strength of normal weight aggregate is generally higher as compared to interfacial transition zone (ITZ) and matrix. However, LWA acts as a weakest source of strength in the LWAC and it can significantly affect the elastic and mechanical properties of lightweight concrete [24]. Past studies investigated the aggregates properties and their effects on the properties of concrete. It was reported that weakest component of the concrete determines its strength. If aggregate is strongest component of concrete mixture, forces are transferred through the aggregate and matrix. However, stress is transmitted through the cement matrix and cracks are spread through the aggregate if LWA is weakest constituent in comparison with matrix. Hence, it was concluded that LWA is a weakest link as compared to ITZ in the LWAC [25–27].

Production of lightweight concrete having the self-flowing properties is a challenging task when employing the high proportion of lightweight aggregate. The formulated concrete mixtures are prone to segregation and bleeding. Lightweight concrete with the density in range of 800–1300 kg/m^3 are normally used only for insulation purposes due to their lower mechanical properties as compared to normal weight concrete. Most of the studies focused of lightweight concrete to be used either as structural materials having high strength or non-structural materials having low thermal conductivity. The balance between the thermal and mechanical properties is not discussed. Also, the available knowledge regarding the thermal properties of lightweight aggregate concrete is not sufficient. It can be observed from the Fig. 1 that high proportion of studies have investigated only thermal conductivity of cement and concrete in details [28]. Contrarily, there are only few studies are available on the thermal properties (volumetric specific heat capacity or thermal mass, thermal diffusivity and thermal resistivity). Hence, the main objective of this research is to formulate self-flowing and an energy efficient low-density lightweight concrete having density in the range of 800–1300 kg/m^3 and to investigate its thermal properties. The formulated LAFC will balance the mechanical and thermal properties and aimed to be utilized both for structural and insulation purposes. The combination of low-density ECA aggregate (335 kg/m^3) and stable foam (180 kg/m^3) was used to produce low-density lightweight aggregate foamed concrete. ECA aggregate had highly porous structure (macropores ranging from 0.1 mm to 2 mm), whereas as foaming agent tends to form micropores inside the concrete. A stable foam was used to improve the homogeneity and avoid the segregation and bleeding of lightweight concrete. The produced concrete demonstrated considerably superior thermal and mechanical properties as compared to previous studies for the same range of density. Mix design of concrete was carried out for the different volume of expanded clay lightweight aggregate (ECA) ranging from 20.1% to 49.4%. SF was also incorporated to check its effect on the properties of LAFC. Workability, mechanical, thermal, hygroscopic and microstructural properties of LAFC were investigated for the characterization purpose.

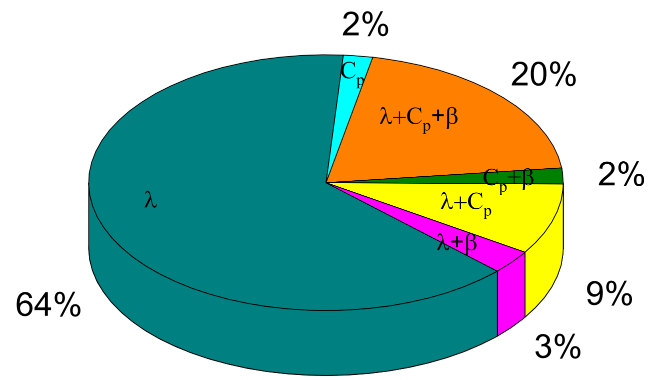

Fig. 1. Proportion of measured thermal properties of cement and concrete (λ – thermal conductivity, C_p – specific heat capacity, β – thermal diffusivity).

2. Materials and methods

2.1. Raw materials

Several LAFC mixtures were prepared by mixing the following raw materials; ordinary Portland cement (OPC) as cementitious materials, ceramsite based expanded clay aggregate (ECA) as lightweight aggregate, uncompacted silica fume (SF), animal protein-based foaming agent, Polycarboxylate superplasticizer (SP) and water. SP was in the solid form with the chloride content less than 0.20%, pH value of 9.0 ± 0.2, bulk density value of 550 kg/m^3, water reduction rate of 20% and completely soluble in the mix. Ordinary Portland cement (OPC) with a 28-day compressive strength of 55.5 MPa was used. The silica fume was obtained from Elkem Materials Co., Ltd with a SiO_2 content of 92.4%. ECA made by heating around 1200 °C was transported from Shandong province of China. Photograph and SEM images of SF, cement, foam and ECA are shown in the Fig. 2. It can be observed that ECA exhibits highly porous structure. The chemical composition of OPC and SF is given in the Table 1. The physical properties of lightweight aggregate are given in Table 2.

2.2. Mixtures preparation

LAFC mixtures were prepared by mixing the OPC, SF, ECA, foaming agent, superplasticizer and water in various proportions. Four mix proportions were designed to prepare the foamed concrete of different densities. LAFC mixtures with the targeted densities of 800 kg/m^3, 1000 kg/m^3, 1200 kg/m^3 and 1300 kg/m^3 were prepared with 49.4, 43.7, 343 and 20.1% volumes of ECA respectively. For each LAFC mixture, OPC was replaced with the 5% and 10% SF to investigate the influence of SF on the physical, mechanical, sorption, thermal and microstructural properties of LAFC. The volume of foam was kept equal to 25% of total volume for each concrete mixture. Ratio of foaming agent to water was 1:40 to prepare the foam, which produced the foam of density nearly 180 kg/m^3.

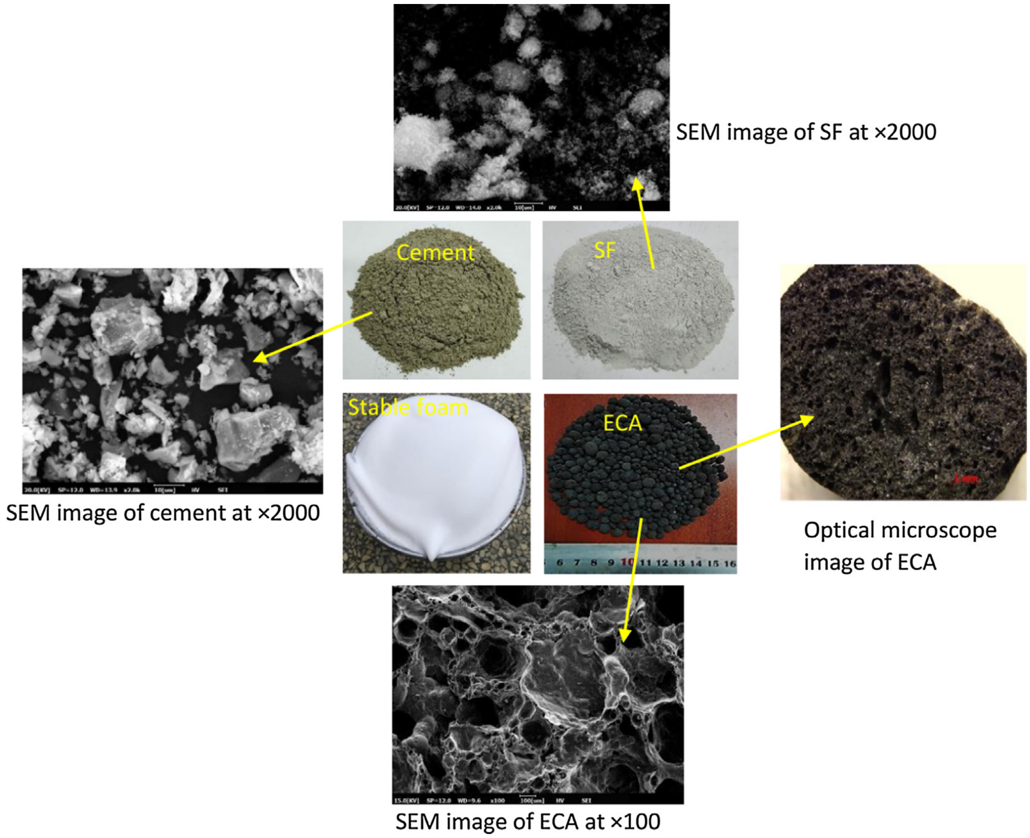

Fig. 2. Constituents of Lightweight aggregate foam concrete mixtures.

Table 1
Chemical composition of cementitious materials.

Raw material	Mass fraction of the sample (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	(MgO	Na_2O	K_2O	SO_3	LOI
OPC	21.6	4.13	4.57	64.44	1.06	0.11	0.56	1.74	0.76
SF	92.4	0.8	0.5	0.91	0.27	–	–	–	2

Table 2
Physical properties of ECA.

Physical property	ECA
Bulk density (kg/m^3)	335
Apparent density (kg/m^3)	525
Water absorption (%)	22.1
Cylindrical compressive strength (MPa)	0.9
LOI (%)	0.06

Water to binder (OPC + SF) ratio of 0.3 was used for all concrete mixtures. The amount of superplasticizer was varied between 0.2 and 0.25% of binder mass to achieve the flowable concrete mixtures. Mix proportions of LAFC mixtures are given in Table 3. All concrete mixtures were prepared in the following order. Firstly, OPC was introduced in the mixing container and mixing was carried out at a high speed of 950 rpm by vertical axis planetary concrete mixer with the gradual addition of water. Secondly, SF was added into mixer with the continuous mixing at high speed. Thirdly, SP was added into mixture and mixing process was continued at high speed for at least 5 min to achieve the homogenous and uniform slurry. After that, premixed foam (Fig. 2) was collected from the foaming machine and introduced into mixture. Finally, lightweight aggregate (ECA) was added and stirring process was further continued for 1 min. Workability of each concrete mixture was evaluated by standard slump cone test method. Concrete cube samples of 100 × 100 × 100 mm^3 size were cast to determine the physical, mechanical, sorption and thermal properties of LAFC. All the concrete samples were removed from the molds after 24 h of casting and immersed in curing water tank for 28 days. Samples were taken out from water at designated ages to determine the mechanical properties. The temperature and relative humidity of laboratory were 23 ± 2 °C and 50 ± 3% respectively.

2.3. Testing methods

Flowability, Mechanical, thermal, sorption and microstructural properties were determined to investigate the fresh and hardened properties of LAFC mixtures. Fresh properties of mixtures were established through the slump flow test for self-consolidating concrete and fresh density tests according to ASTM C1611/C1611M and ASTM C138. Slump value is the vertical fall in the height of concrete mixture once slump cone is lifted vertically. Slump flow diameter is the spread of the concrete mixtures when the slump cone is lifted. It is used to measure the viscosity and resistance to segregation of self-flowing concrete. The concretes are classified in to the different visual stability index (VSI) based on their flow

Table 3
Mix proportion and fresh properties of LAFC mixtures.

Target fresh density, ρ_t (kg/m^3)	Mix ID	OPC (%)	SF (% of OPC wt)	ECA (%)	Foam (%)	water (%)	Slump value (mm)	Flow dia (mm)	Fresh density, ρ_f (kg/m^3)	Dry density, ρ_d (kg/m^3)	ρ_f/ρ_t
800 ± 5%	800-0SF	13.2	0	49.4	25	12.3	260	603	788	739.04	1.02
	800-5SF	12.54	5	49.4	25	12.3	250	571	814	777.99	0.98
	800-10SF	11.88	10	49.4	25	12.3	245	560	835	799.08	0.96
1000 ± 5%	1000-0SF	16.2	0	43.7	25	15.08	270	589	995	971.79	1.01
	1000-5SF	15.39	5	43.7	25	15.08	250	553	1030	1016.68	0.97
	1000-10SF	14.58	10	43.7	25	15.08	244	546	1043	1025.26	0.96
1200 ± 5%	1200-0SF	21.2	0	34.3	25	19.5	263	620	1150	1099.74	1.04
	1200-5SF	20.14	5	34.3	25	19.5	250	600	1181	1116.30	1.02
	1200-10SF	19.08	10	34.3	25	19.5	246	550	1206	1167.11	1.00
1300 ± 5%	1300-0SF	31	0	20.1	25	24.3	260	620	1244	1174.12	1.05
	1300-5SF	29.45	5	20.1	25	24.3	255	596	1285	1228.71	1.01
	1300-10SF	27.9	10	20.1	25	24.3	250	540	1352	1315.69	0.96

characteristics. The VSI is established based on whether bleed water is observed at the leading edge of the spreading concrete, or if aggregates pile at the center. VSI values range from 0 for "highly stable" to 3 for unacceptable stability.

Results of standard slump and fresh density tests are given in Table 3. Compressive strength test on all LAFC specimens was conducted at the age of 7 d (water-cured), 28 d (water-cured) and 56 d (28 d water-cured & 28 d air-cured) in accordance with the BS EN 206. Specimens were tested by compression testing machine at a displacement rate of 0.02 mm/s. Splitting tensile strength of specimens was tested at the age of 28 d as per BIS IS 5816 : 1999 (R2004). All the specimens were loaded at a constant stress rate of 0.6 MPa/min. The specimens were moist cured for the first 7 days followed by the air-dry condition for 21 days at the temperature and relative humidity of 23 ± 2 °C and 50 ± 3% respectively. Compressive and splitting tensile strength tests were carried out using the compression testing machine (Instron 8501, hydraulic servo-controlled machine). Strength for each concrete mixture was determined by taking the average of three cube samples. Setup of compressive and tensile strength test is shown in the Fig. 3a and b.

Thermal conductivity (λ is one of the most important parameters to evaluate the thermal properties of a materials. It is an intrinsic property of a materials and governed by its internal structure of material. Thermal conductivity of all LAFC mixtures was determined using the TC3000E thermal conductivity meter in accordance with the ASTM C3111. TC3000E works on the principle of transient hotwire method and is capable of measuring the thermal conductivity in the range of 0.001 W.m^{-1} K^{-1} to 10 W.m^{-1} K^{-1} with the reproducibility and accuracy of ±3%. Concrete cubes were first dried in an oven at 70 °C until the constant weight was achieved. Samples were then cooled in an air-conditioned room to achieve the room temperature of 25 °C. Sensor was put between the two cubic specimens ensuring the smooth contact of connecting surfaces of two specimens (Fig. 3d). For each concrete mixture, thermal conductivity was calculated by taking the average of eight determinations for two different set of specimens. Volumetric heat capacity also known as thermal inertia is ability of materials to store the heat while undergoing temperature changes. Good thermal mass material absorb the heat during the day and release it slowly over the night, which plays an important role to improve the thermal comfort in buildings. Volumetric specific heat capacity, thermal diffusivity and thermal resistivity was measured with the help of Decagon KD2 Pro as per ASTM D5334 (Fig. 3e). The SH-1 dual needle sensor was used to measure the thermal properties of LAFC mixtures. The holes to insert the sensor were drilled with the help of pilot pins in the fresh concrete mixtures.

The permeable porosity of concrete samples was determined by the vacuum saturation technique in accordance with the ASTM C 1202-12, which has been mentioned one of the most efficient technique for the porosity determinations [29]. First, all the specimens were oven dried at 70 °C until they achieved the constant weight. Secondly, specimens were placed in the vacuum desiccator for 3 h. Finally, de-aired distilled water was used to fill the desiccator. The porosity of the specimens was then calculated by using the Eq. (1).

$$\varphi(\%) = \frac{(W_{sat} - W_d)}{(W_{sat} - W_{sub})} \quad (1)$$

where, φ = porosity, W_{sat} = saturated surface dry mass of sample in air, W_d = oven dry mass sample, W_{sub} = submerged mass of sample in water

For the Sorptivity test, 100-mm cube specimens were oven dried to constant mass at the 70 °C. The sides of specimens were greased and covered with the water-resistant aluminum foil so that specimen could absorb water only vertically. The level of water was maintained 5 mm above the base of specimens throughout the test. Specimens were weighed at the time intervals of 4, 9, 16, 25, 36, 49, 64, 120, 360 and 1440 min to determine the gain in weight due to water absorption. The similar detailed procedure is explained elsewhere [30].

Water absorption by total immersion of specimens has been also accepted as a relevant condition for thermal insulation products. EN 12087:2013 [31] was followed to determine the water absorption by complete immersion. Specimens were oven dried to constant mass and immersed in water. The amount of water absorbed was calculated by the Eq. (2)

$$\alpha = \frac{m_7 - m_{dry}}{V} \times \frac{100}{\rho_w} \quad (2)$$

where, α = water absorption (Volume percent), m_7 = is the mass of specimen after 7 days of immersion in water (kg), m_{dry} = is the initial mass of specimen at the start of experiment (kg), V = is the initial volume of specimen (m^3), ρ_w = is the density of water (kg/m^3), ω = water absorbed volume percent

Morphology of cement, SF, ECA and LAFC mixtures was observed with the SEM COXEM EM-30 plus. The samples for SEM were obtained from the cubic concrete samples dried in oven after 28 days of hydration. All the samples were gold coated with the help of SPT-20 digital ion coater in order to make them electrically conductive.

Fig. 3. Testing setup for (a) compressive strength (b) splitting tensile strength (c) Distribution of ECA in LAFC sample (d & e) thermal properties measurements with TC300E and Decagon KD2 Pro.

3. Results and discussion

3.1. Fresh properties of LAFC mixtures

Workability of LAFC mixtures was determined in term of slump value and flow diameter. Image of measurement of slump value flow diameter of prepared self-flowing LAFC mixture is shown in the Fig. 4. Normally, the stability of self-flowing concrete is assessed by the visual stability index (VSI) values (0 for highly stable and 3 for highly unstable) as mentioned in ASTM C1611/C1611M. Fig. 4 shows no evidence of segregation or bleeding and hence, foamed concrete prepared in this study had VSI value of 0 and was considered as highly stable. Addition of thick and stable foam combined with the lightweight aggregate helped to produce stable LAFC mixtures without segregation and bleeding. Distribution of expanded clay lightweight aggregate (ECA) in the hardened lightweight foamed concrete for the different mixtures is shown in the Fig. 3c and it can be seen that ECA is uniformly dis-

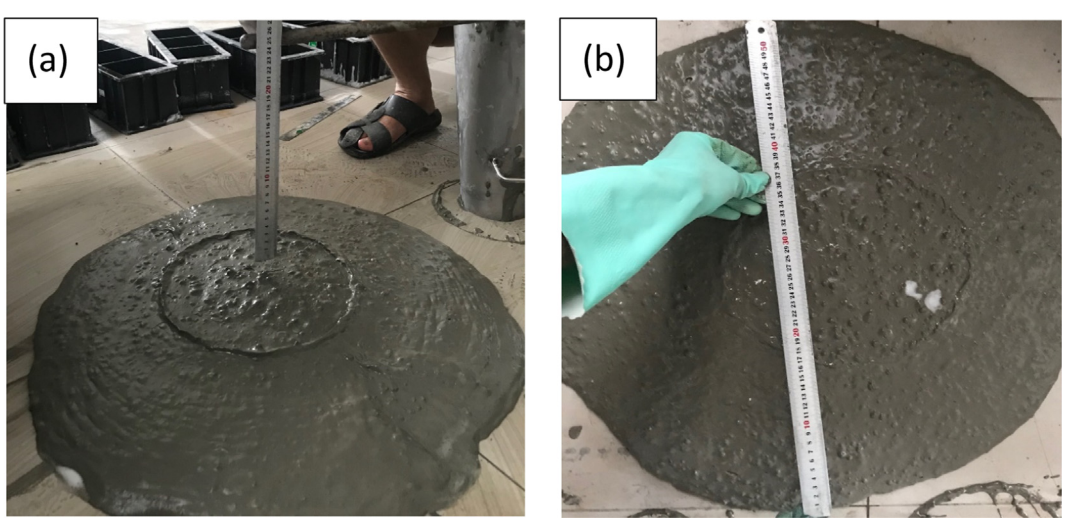

Fig. 4. Measurement of slump test parameters of lightweight aggregate foamed concrete (a) slump value (fall in slump); (b) slump flow diameter.

tributed throughout the hardened concrete specimens in all concrete mixtures which also confirmed the homogeneity of prepared fresh mixture and right approach to utilize the foaming agent to formulate the concrete mixture with the high flowing properties. Results of standard slump test methods are shown in the Fig. 5 and Table 3. Slump values of all concrete mixtures were in the range of 245 mm–270 mm whereas the values of flow diameter of LAFC mixtures were in the range 546 to 620 mm. Volume of foam was kept 25% for the all LAFC mixtures, whereas amount of water and superplasticizer was changed to obtain the required flowability. Change in the volume of ECA had negligible effect on the slump value (Fig. 5a) and flowability (Fig. 5b) of LAFC. Incorporation of SF reduced the slump value and flowability of LAFC mixtures. Previous study by Wang and Li [32] also reported that addition of SF can decline the flowing properties of concrete. However, all concrete mixtures exhibited self-flow properties and meet the flow requirement of ASTM C1611/C1611M (500–750 mm) and The European Guidelines for Self-compacting Concrete (550–750 mm) [33]. Influence of ECA volume on the fresh density of LAFC is shown in the Fig. 5c. It can be observed that increased in the volume of ECA greatly reduced the fresh density of LAFC associated with the lower density of ECA in comparison to the binder. The fresh density of LAFC mixtures was lowered down from 1352 to 788 kg/m^3 when ECA volume was increased from 20.1 to 49.4%, which was associated with the high porous structure of ECA. However, incorporation of SF slightly increased the density of concrete specimen due to its higher pozzolanic reactivity and dense packing characteristics. Moreover, ratio of target density and fresh density of LAFC mixture was very close to 1, which confirmed that mix design and mixing procedure adopted to formulate LAFC were accurate.

3.2. Compressive strength

Result of compressive strength for the different densities of LAFC mixtures is plotted in the Fig. 6a. It can be observed that compressive strength was gradually increased with the increase in curing age from 7 d to 56 d, which indicated the continuous formation of hydration products. Increase in the volume of ECA progressively decreased the density and strength. All the concrete mixtures gained 70–90% of their 28 days strength during the first 7 days, which shows that most of the hydration process was completed during the first 7 days. Compressive strength of 800-0SF, 800-5SF and 800-10SF LAFC mixtures tested at the 28 d was 6.5, 8.4 and

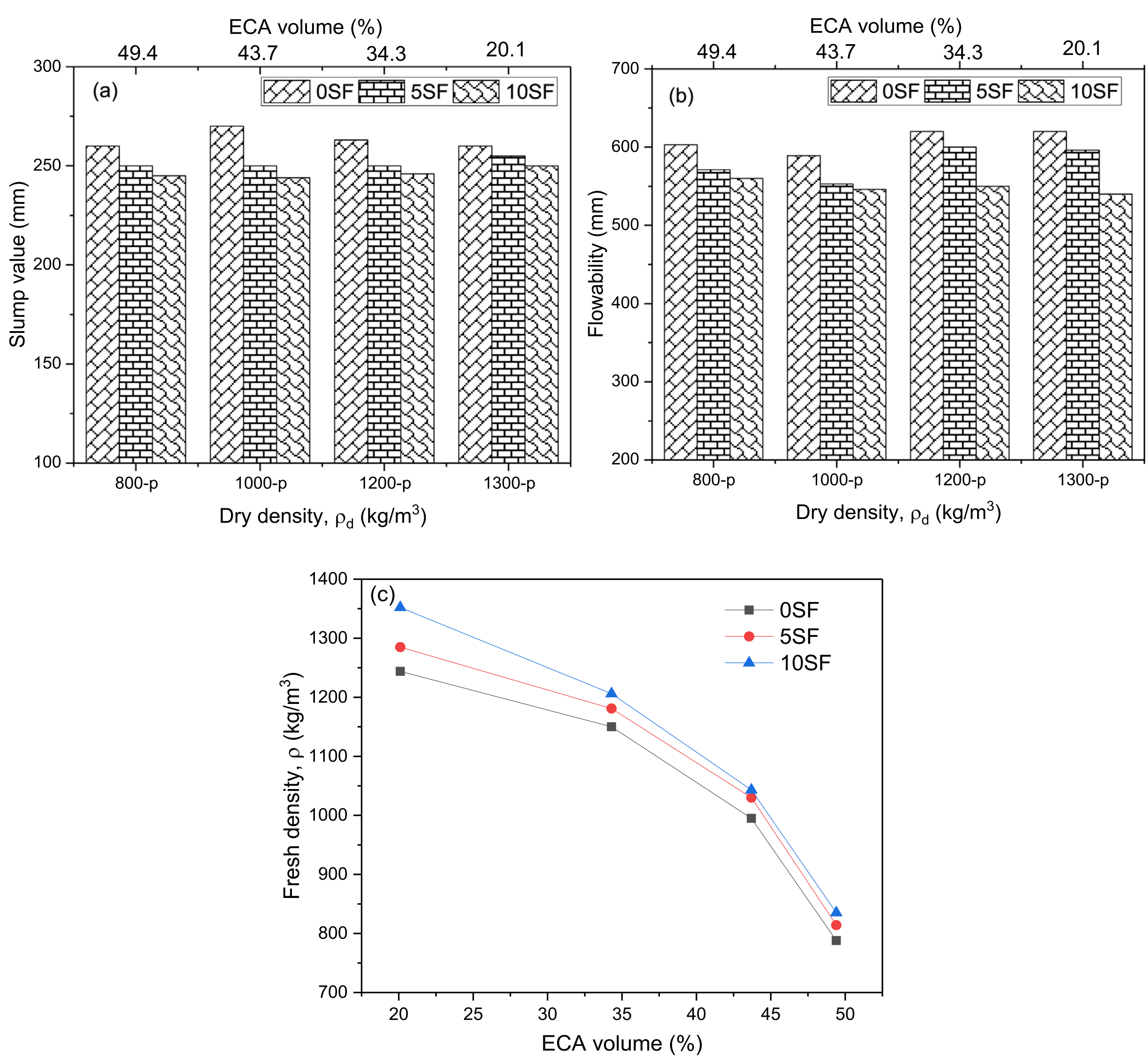

Fig. 5. Fresh properties of lightweight aggregate foamed concrete (a) slump value (b) flowability (c) effect of ECA volume on the fresh density of concrete.

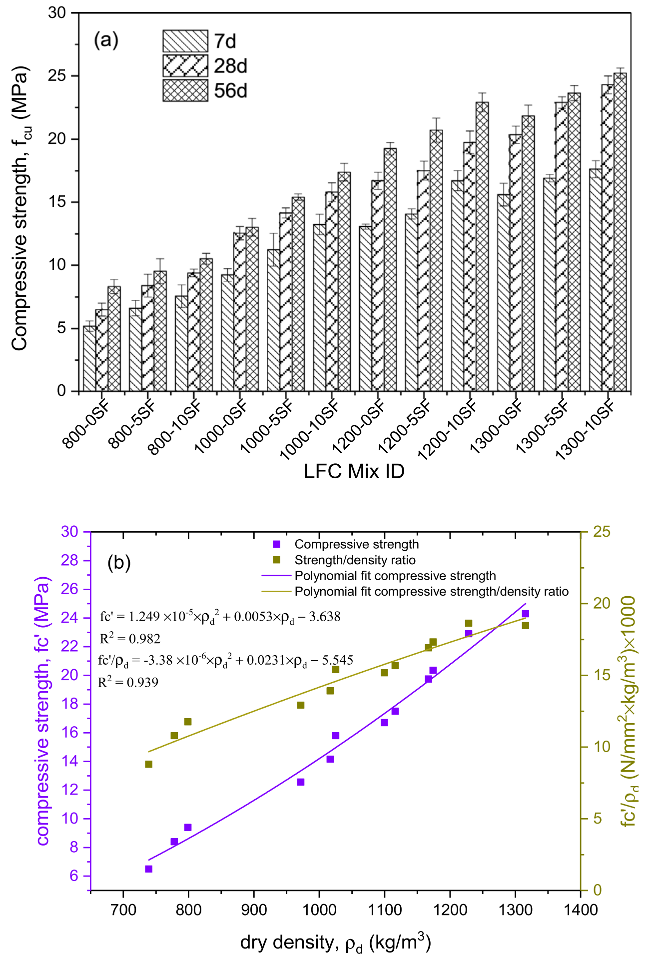

Fig. 6. (a) Compressive strength of different LAFC mixtures at 7, 28 and 56 days (b) relationship between strength and density.

9.4 MPa, and for the mixtures 1000-0SF, 1000-5SF and 1000-10SF tested at the 28 d, it was 12.56, 14.15 and 15.8 MPa respectively. Similarly, compressive strength for 1200-0SF, 1200-5SF and 1200-10SF mixtures was 16.7, 17.5 and 19.75 MPa, and for the mixtures 1300-0SF, 1300-5SF and 1300-10SF, it was 20.35, 22.9 and 24.3 MPa respectively. Obviously, increase in the compressive strength was strongly linked to volume of ECA and incorporation of SF. Lower the volume of ECA, lower will be the total air-voids and higher will be the compressive strength of LAFC. Hence, compressive strength increased progressively with the increase in density of mixtures, which was in agreement with the previous findings of Alengaram et al. [34]. Addition of SF also imparted positive effect on the compressive strength and significant increase in compressive strength was observed by increasing the SF from 0% to 10%. The increase in compressive strength due to addition of SF was associated with its chemical and physical effects. Chemically, SF can react with the hydration products ($Ca(OH)_2$) of OPC and form extra calcium silicate hydrate gel (C-S-H), which can densify the structure of cement and improve mechanical properties of LAFC. Recently, Gökçe et al. [6] also investigated the influence of fly ash and silica fume on the strength of foamed concrete and observed that foamed concrete mixtures containing SF demonstrated better mechanical performance in comparison with mixtures containing fly ash. For the LAFC mixtures with the densities 800, 1000, 1200 and 1300 kg/m^3, addition of 10% SF resulted in 44.6%, 25.7%, 18.2% and 19% increase in strength as compared to LAFC mixtures without SF. Lowest compressive strength at the 28 and 56 days was exhibited by LAFC mixtures 800-0SF which was 6.5 and 8.32 MPa, and highest compressive strength was exhibited by 1300-10SF mixture which was 24.3 MPa and 25.3 MPa respectively.

The relationship of density, compressive strength and strength/density is shown in the Fig. 6b. It can be seen that density has a direct relationship with the strength (higher the density, higher will be the strength). Increase in the volume of ECA from 20.1% to 49.4% tended to decrease the density of LAFC mixtures (from 1315 to 739 kg/m^3) and hence, compressive strength of LAFC specimens was due reduced accordingly (from 24.3 MPa to 6.5 MPa). Relationship derived from the polynomial regression analysis between the strength and density had the correlation factor of 0.982, which confirms the strong relation between the density and compressive strength of LAFC mixtures. Strength/density ratio is an important factor for the design of lightweight concrete. Strength/density ratio of formulated LAFC mixtures with the strength higher than 15 MPa (see Section 3.7) was in the range of 15.4–18.5, which was more than 50% higher than that of normal weight concrete (NWC) [35]. Moreover, density of formulated structural grade concrete mixtures was approximately 41–50% lower as compared to NWC, which is of great advantageous as structural members prepared with these concrete mixtures would be helpful to reduce the overall cost of concrete structure.

3.3. Splitting tensile strength

Indirect tensile strength of concrete can be measured by testing the specimen for splitting tensile strength [36]. Splitting tensile strength of LAFC designed for the different densities of LAFC is presented in the Fig. 7a. It is very obvious that tensile strength of concrete specimens was increased by increasing their density. Testing setup and failure pattern of LAFC specimens tested for splitting tensile strength is shown in the Fig. 2b and c respectively. The specimens with the lower density contained higher volume of ECA and hence, higher air void contents due to highly porous structure of ECA was responsible for the decrease in the strength. Moreover, addition of SF had positive effect on the splitting tensile strength of all LAFC mixtures and strength was gradually increased by increasing the SF from 0% to 10%. For example, tensile strength of 800-0SF, 800-5SF and 800-10SF was 0.52, 0.69 and 0.78 MPa respectively, which shows that addition of 5% and 10% SF increased the tensile strength of concrete by 32 and 50%. Maximum and minimum tensile strength was shown by the 1300-10SF and 800-0SF respectively, which was 1.63 MPa and 0.52 MPa. The ratio of tensile strength to compressive strength for expanded clay aggregate was 6.4–8.4%. Results of splitting tensile strength were compared with the equations proposed by different researchers for lightweight concrete. (Eq. (3) proposed by Shafigh et al. [37], Eq. (4) proposed by Neville and C.F.M. Code [38,39], and Eq. (5) proposed by Shafigh et al. [40]). Eq. (6) is proposed for lightweight concrete based on ECA aggregate for the obtained experimental data and comparison with previous studies is shown in the Fig. 7b.

$$f_t = 0.20\sqrt[3]{f_{cu}^2} \quad (3)$$

$$f_t = 0.23\sqrt[3]{f_{cu}^2} \quad (4)$$

$$f_t = 0.27(f_{cu}^{0.63}) \quad (5)$$

$$f_t = 0.178\ \sqrt[3]{f_{cu}^2} \quad \text{Proposed Eq. for LAFC based on ECA} \quad (6)$$

Comparison of results indicate that Eq. (6) shows lower values of tensile strength values as compared to Eqs. (4) and (5) proposed on the base of experimental data. Whereas, Eq. (3) and proposed

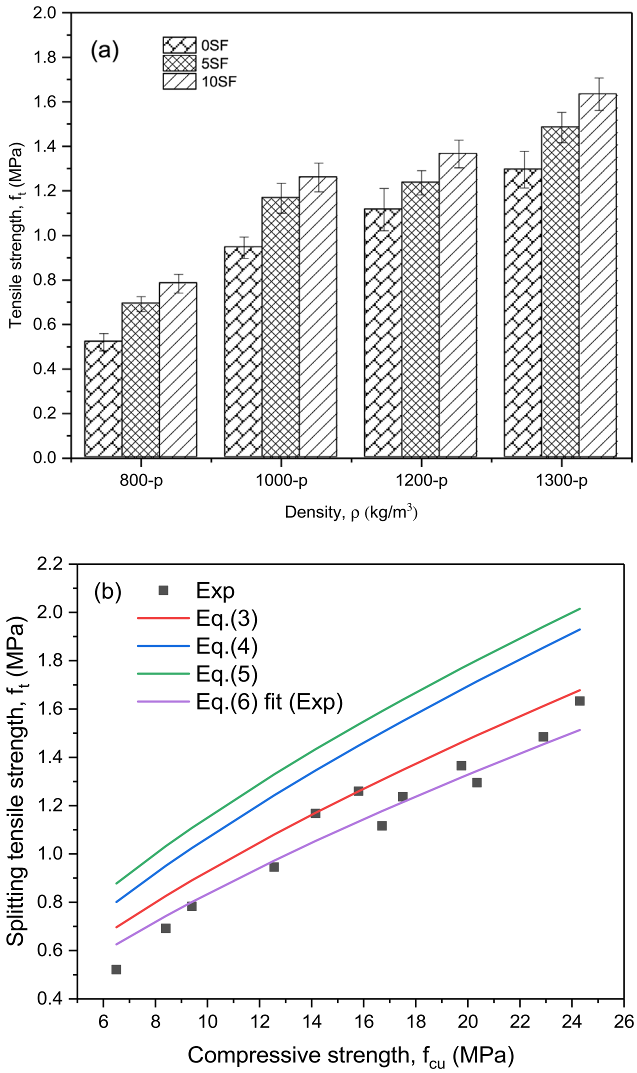

Fig. 7. (a) Splitting tensile strength of LAFC mixtures at 28 days (b) relationship between tensile strength and compressive strength of LAFC mixtures.

Eq. (6) predicted comparatively close results of tensile strength. The differences in the results can be linked to the lower density of lightweight aggregate (low density of ECA equal to 335) and concrete and incorporation of high volume of foam as compared to other studies.

3.4. Porosity of LAFC mixtures

Porosity of LAFC mixtures was determined in accordance with the ASTM C1202-12 and results are shown in the Fig. 8 and Table 4. Effect of SF on the porosity of LAFC mixtures is shown in the Fig. 8a. It can be seen that addition of SF reduced the porosity of LAFC mixtures, which was associated with the physical and chemical effect of SF. For the same density of LAFC mixtures, total pore volume was slightly decreased when the amount of SF was increased from 0% to 10%. Moreover, these findings were also in agreement with the results of air-voids structure observed by SEM analysis (Fig. 14). It is obvious from the Fig. 8b that the dry density influences the porosity of LAFC specimens to a great extent. Porosity of LAFC specimens was gradually reduced from 70% to 34% when density was increased from 800 kg/m^3 to 1300 kg/m^3. Hence, decrease in density from 1300 kg/m^3 to 800 kg/m^3 enhanced the porosity of LAFC by 48%. Total volume of ECA played an important role to change the porosity of LAFC; higher the volume of ECA, higher will be the porosity of LAFC. Liu et al. [41] also confirmed the inverse relation of porosity and dry density of LAFC. LAFC mixtures with the density of 1300 kg/m^3 were found to have similar porosity in the range of 34–37% as compared to LAFC with the density 1314 kg/m^3 reported by Liu et al. [41]. Apart from these factors, tortuosity, size and distribution of pores, thickness and nature of interfacial transition zone, and distribution and type aggregate also affect the porosity of concrete [42]. Neville [43] reported that mechanical strength of concrete is largely affected by the overall volume of voids. Higher the volume of voids, lower will be density and compressive strength. This effect of porosity on the compressive strength of LAFC can be observed from Fig. 6, where compressive strength was decreased with the decrease in the density (lower density ~ higher porosity).

3.5. Sorptivity

Hygroscopic properties of a construction material greatly influence the indoor relative humidity. Sorptivity results for LAFC mixtures as a function of water uptake vs time and sorption coefficient vs percentage of SF are plotted in the Figs. 9 and 10. Water uptake (i) had a direct relationship with the square root of time. For the LAFC with density 800 kg/m^3, increase in the amount of SF from 0% to 10% decreased the value of water uptake from 28.2 to 23.3 kg/m^2. Water uptake coefficients of LAFC mixtures with 800, 1000, 1200 and 1300 kg/m^3 containing 0%SF were 28.19, 21.63, 19.0 and 16.73 kg/m^2 respectively, which shows that water absorption was gradually reduced with the increase in the density. Concrete mixtures containing 5% and 10% SF showed less water uptake values as compared to LAFC mixtures without SF as shown in the Fig. 9. The correlation coefficient (R^2 in Table 4) for the all LAFC mixtures exceeded than 0.94, which evidenced the strong relationship between i and time. Sorptivity of LAFC can be estimated by taking the slope of linear fitting curve of water-uptake coefficient plots and results of sorptivity are given in the Fig. 10. It can be observed that density had an inverse correlation with the sorptivity of concrete. For the 0%SF, sorption coefficient (ω) was reduced from 2.56 to 1.69 kg/m^{-2} min$^{-0.5}$ when density was increased from 800 to 1300 kg/m^3. Same trends of decrease in ω value was shown by mixtures containing 5% and 10%SF. However, keeping the density of LAFC mixture constant, ω value was decreased by increasing the amount of SF from 0% to 10%. For example, sorption coefficients for 1300-0SF, 1300-5SF and 1300-10SF mixtures were 1.69, 1.53 and 1.47 kg/m^{-2} min$^{-0.5}$ respectively. Hence, density and SF had an inverse relationship with the sorptivity of LAFC. This phenomenon can be explained from the findings of SEM results and porosity of LAFC mixtures discussed in the Sections 3.8 and 3.4. Total volume of pores was reduced with the increase in the density and percentage of SF, which in turn made the structure of LAFC denser and reduced the capillary suction.

3.6. Water absorption

Water absorption of LAFC specimens for different densities of LAFC specimens is shown in the Fig. 11. The water absorption of LAFC mixtures had inverse relationship with the density. For the 0% SF content, water absorption of LAFC mixtures with densities 800 kg/m^3, 1000 kg/m^3, 1200 kg/m^3 and 1300 kg/m^3 was 23.83, 17.40, 13.55 and 10.64 vol% respectively, which indicates that increase in the density from 800 kg/m^3 to 1300 kg/m^3 reduced the water absorption by 55.4%. Hence increase in the density reduced the water absorption of LAFC, which was attributed to lower volumes of pore due to low fraction of ECA. For the LAFC with the density 800 kg/m^3 containing 0, 5 and 10% SF, water

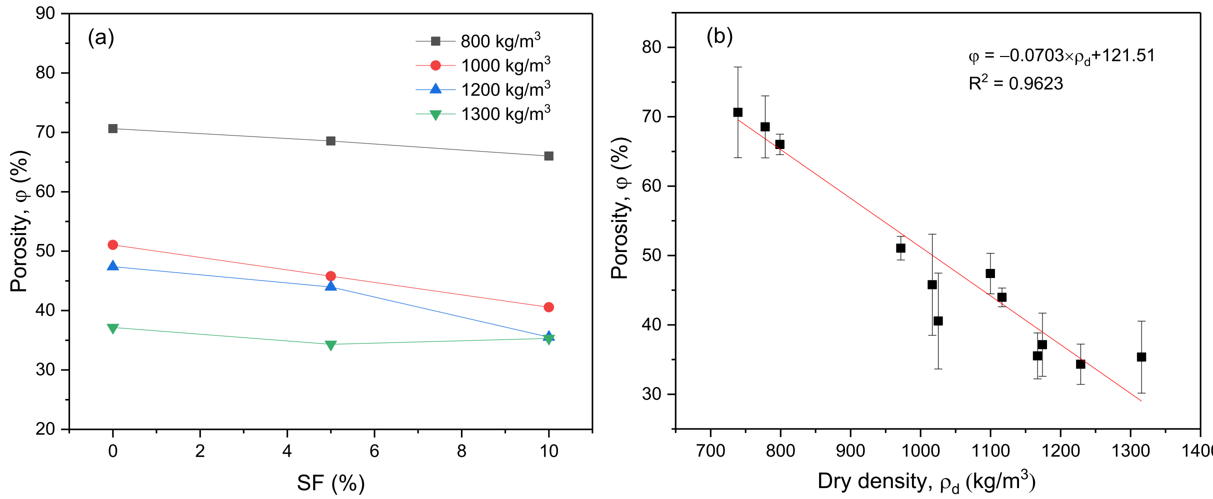

Fig. 8. (a) Effect of SF on the porosity of LAFC mixtures, (b) porosity of LAFC mixtures as a function of density.

Table 4
Mechanical and sorption properties of LAFC mixtures.

Mix ID	Dry density (kg/m^3)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Porosity (%)	Sorption coefficient kgm^{-2} min$^{-0.5}$	R^2
800-0SF	739.04	6.50	0.52	70.63	2.56	0.937
800-5SF	777.99	8.40	0.69	68.54	2.33	0.991
800-10SF	799.08	9.40	0.78	66.02	2.18	0.966
1000-0SF	971.79	12.56	0.95	51.06	2.11	0.969
1000-5SF	1016.68	14.15	1.17	45.79	2.08	0.980
1000-10SF	1025.26	15.80	1.26	40.56	1.83	0.987
1200-0SF	1099.74	16.70	1.12	47.40	1.92	0.984
1200-5SF	1116.30	17.50	1.24	43.96	1.78	0.954
1200-10SF	1167.11	19.75	1.37	35.53	1.64	0.967
1300-0SF	1174.12	20.35	1.30	37.15	1.69	0.954
1300-5SF	1228.71	22.90	1.48	34.32	1.53	0.948
1300-10SF	1315.69	24.30	1.63	35.32	1.47	0.939

absorption was 23.93, 20.30 and 18.91 vol% respectively, which shows the increase in amount of silica from 0% to 10% reduced the water absorption of LAFC mixture by 26.5%. Other lightweight LAFC mixtures also exhibited the same trends in the decrease in water absorption, when SF was replaced with the cement. Hence, increase in the amount of SF and density reduced the water absorption of LAFC. In fact, the concrete specimens with the low density contained higher volume of lightweight aggregate (49.4%) and air-voids, which can absorb more water due to their highly porous structure.

3.7. Thermal properties

Thermal insulation properties were investigated through thermal conductivity, volumetric specific heat capacity, specific thermal resistance, thermal diffusivity and thermal inertia of LAFC mixtures. Thermal insulation plays a key role in the reduction of power requirement of buildings and hence less greenhouse gases are emitted for the building with good thermal properties. Thermal conductivity of any material is a quantity of heat that can pass by a unit thickness in the direction perpendicular to unit surface area because of temperature gradient under the give condition [44]. Thermal conductivity of LAFC specimens plotted as a function of SF dosage is plotted in the Fig. 12a. For the same density, incorporation of SF increased the thermal conductivity (Fig. 12a), as λ value for LAFC mixtures with the density 800 kg/m^3 was 0.228, 0.232 and 0.235 W/m.K for the 0%, 5% and 10% SF respectively. The increase in the thermal conductivity due to addition of SF is associated with the densification effect. Thermal conductivity of LAFC specimens increased with the increase in density from 800 to 1300 kg/m^3 for the same content of SF, which was attributed to the lower volume of ECA in high-density concrete (21.1%) than that of lower density (49.4%). For example, λ value for LAFC with 800, 1000, 1200 and 1300 kg/m^3 density was 0.235, 0.325, 0.386 and 0.448 W/m.K respectively for the 10%SF dosage. Fig. 12b shows the relationship between the thermal conductivity, compressive strength and dry density of LAFC mixtures. The correlation factors (R^2 = 0.9820, R^2 = 0.9651) depict that there is a strong relationship of thermal conductivity with the compressive strength and density, and that thermal conductivity is directly proportional to compressive strength and density of concrete. High volume of the aggregate decreases the density of LAFC mixtures due to its highly porous structure (Fig. 14) and hence reduced the thermal conductivity (Fig. 12b). Saygili and Baykal [45] also reported that increase in the void ratio decreased the density of concrete which in turn lowers the thermal conductivity. As air is poorest conductor in comparison with the liquids and solids, it will contribute to decrease the thermal conductivity of porous concrete [46]. It can be deduced that the increase in the volume of ECA from 20% to 50% decreased the thermal conductivity of LAFC mixtures and hence resulted LAFC mixture demonstrated excellent thermal insulation properties. Moreover, thermal conductivity of LAFC are compared with the conventional materials used in the construction industry as shown in Table 5 [47]. Lightweight foamed concrete

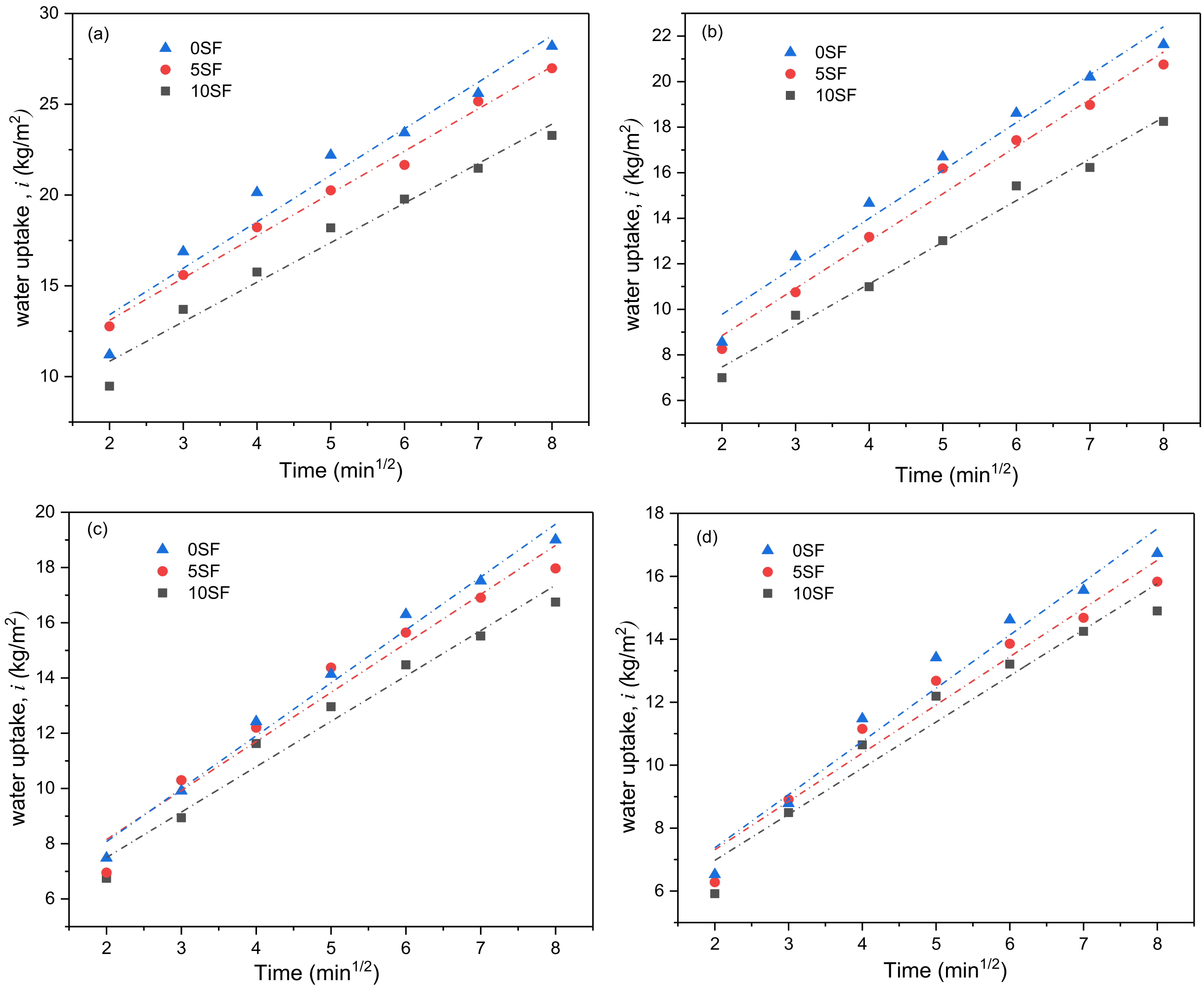

Fig. 9. Water-uptake coefficient vs time relationship (a) 800 kg/m^3 or ECA volume 49.4%, (b) 1000 kg/m^3 or ECA volume 43.7%, (c) 1200 kg/m^3 or ECA volume 34.3%, and (d) 1300 kg/m^3 or ECA volume 20.1%

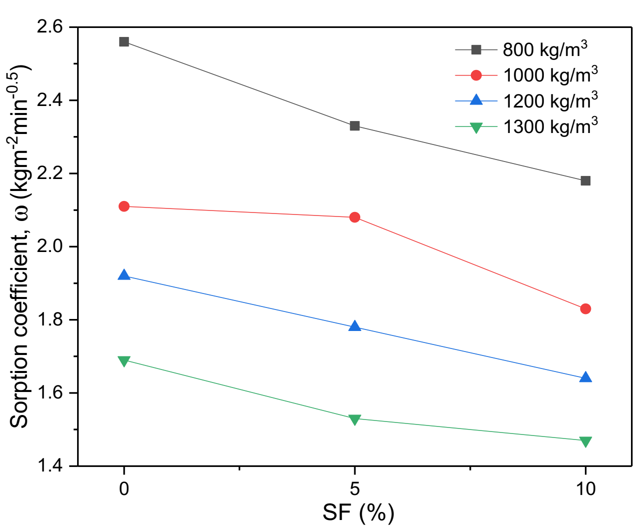

Fig. 10. Sorptivity of LAFC mixtures after 28 days of curing.

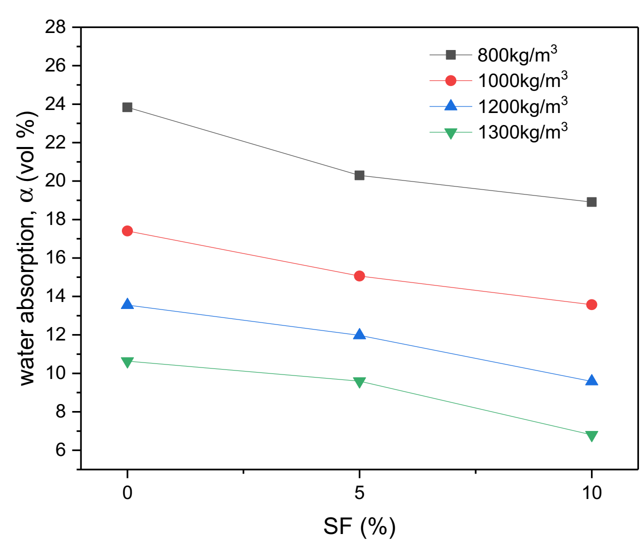

Fig. 11. Water absorption of LAFC mixtures.

showed the better thermal performance as compared to conventional materials for the same densities, which would enable the LAFC to be more a practical and suitable material for energy efficiency. As per RILEM classification [48], concrete with the strength more than 15 MPa can be categorized as Class-I structural grade concrete. Hence, the LAFC mixtures 1000-10SF, 1200-0SF, 1200-5SF, 1200-10SF, 1300-0SF, 1300-5SF and 1300-10SF with the dry density in range of 1025 to 1315.69 kg/m^3 and compressive

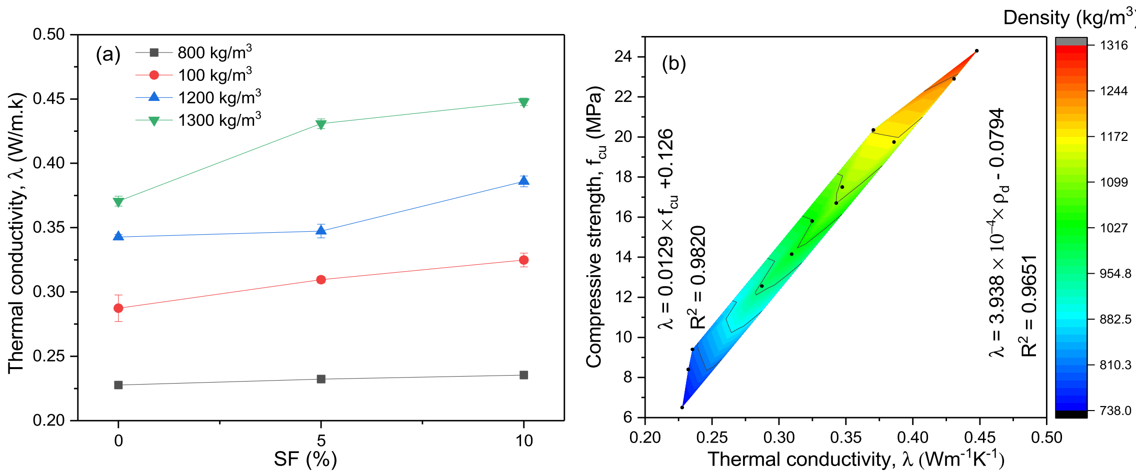

Fig. 12. Thermal conductivity of LAFC concrete (a) thermal conductivity as a function of SF percentage (b) relationship of thermal conductivity, compressive strength and density.

Table 5
Comparison of LAFC thermal conductivity with the alternative materials used in construction industry.

This study	Density (kg/m^3)	λ (W/m.K)	Literature	Density (kg/m^3)	λ (W/m.K)
800-0SF	739.04	0.228	Aerated brick	1350.00	0.43
800-5SF	777.99	0.232	Fire brick	2000.00	1.00
800-10SF	799.08	0.235	Mud Brick	1731.00	0.75
1000-0SF	971.79	0.287	Perforated or solid brick (mediumweight)	1450	0.69
1000-5SF	1016.68	0.310	Perforated or solid brick (lightweight)	0.95	0.41
1000-10SF	1025.26	0.325	Concrete block (hollow mediumweight)	928.00	0.85
1200-0SF	1099.74	0.343	Concrete block (hollow lightweight)	720.00	0.57
1200-5SF	1116.30	0.347	concrete lightweight (solid block)	1400.00	0.63
1200-10SF	1167.11	0.386	Masonry lightweight (airbricks)	1400.00	0.91
1300-0SF	1174.12	0.371			
1300-5SF	1228.71	0.431			
1300-10SF	1315.69	0.448			

strength of 15.8 to 24.3 MPa can be classified as structural grade concrete according to RILEM functional classification of concrete. Whereas, all LAFC mixtures fall under the category of Class-II structural and insulating concrete (Class-II concrete has compressive strength in between 3.5 and 15 MPa and thermal conductivity lower than 0.75 W/m.K). Moreover, concrete with the density 800 kg/m^3 can be classified into Class-III (Class-III concrete has compressive strength in between 0.5 and 3.5 MPa and thermal conductivity lower than 0.30 W/m.K).

Volumetric specific heat capacity of materials (thermal inertia) is its ability to store thermal energy when undergoing temperature change and an important factor for thermal comfort and building energy consumption under the transients conditions. Thermal resistance measure the resistance of any material against the flow of heat for a given temperature difference. The results of specific heat capacity and thermal resistance are plotted as a function of dry density in the Fig. 13 and shown in Table 6. It can be observed that volumetric specific heat capacity is directly related to the density of concrete. Moreover, specific heat capacity of LAFC was slightly lower the normal weight concrete and results were consistent with the literature [49]. Thermal resistance was decreased with the increase in the density of concrete, which was obvious as thermal resistance is reciprocal of thermal conductivity. Thermal diffusivity can be determined form the combination of thermal conductivity and specific heat capacity and results of thermal diffusivity are shown in the Table 6. Thus, the variation in the thermal diffusivity with respect to the density of LAFC are similar to thermal conductivity. Thermal inertia of construction materials plays an important role to level out the indoor temperature variation,

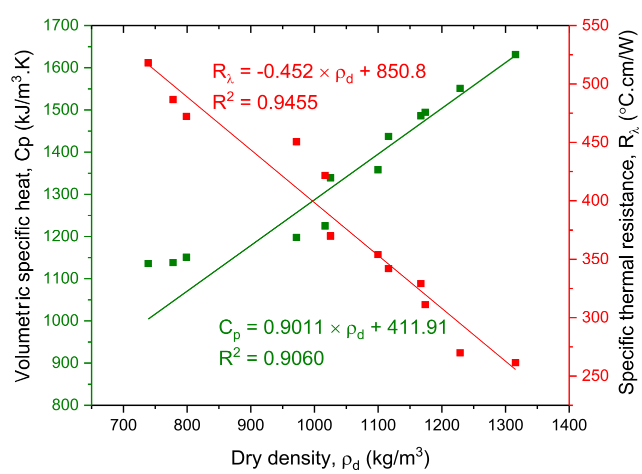

Fig. 13. Volumetric specific heat capacity and thermal resistance of LAFC.

provide better comfort level in the summer and save heating expenses. Commonly, good construction materials for the thermal inertia should have low thermal diffusivity and high thermal inertia. Various materials like aluminum and steel exhibits high thermal inertia and high thermal diffusivity, which means they can accumulate lot of heat energy but release it very quickly also. For an efficient thermal mass, it should store heat during the day time and liberate it slowly when temperature drops in the night [50–52]. The formulated LAFC mixtures exhibited considerably lower

Table 6
Thermal properties of LAFC mixtures.

Mix ID	Dry density (kg/m^3)	Thermal conductivity (W/m.K)	Volumetric heat capacity ($kJ/m^3.K$)	Thermal resistivity (°C.cm/W)	Thermal diffusivity (mm^2/s)
800-0SF	739	0.228 ± 0.00224	1136	518	0.200
800-5SF	778	0.232 ± 0.001	1138	500.3	0.204
800-10SF	799	0.235 ± 0.00262	1151	433.2	0.205
1000-0SF	972	0.287 ± 0.01029	1198	462.6	0.240
1000-5SF	1017	0.310 ± 0.0024	1225	368.4	0.253
1000-10SF	1025	0.325 ± 0.00539	1339	315.7	0.243
1200-0SF	1100	0.343 ± 0.00194	1358	363.7	0.252
1200-5SF	1116	0.347 ± 0.00528	1437	327.9	0.242
1200-10SF	1167	0.386 ± 0.00419	1486	310	0.260
1300-0SF	1174	0.371 ± 0.00386	1494.3	341.9	0.248
1300-5SF	1229	0.431 ± 0.00381	1551	317.9	0.278
1300-10SF	1316	0.448 ± 0.00294	1631	261.5	0.275

thermal diffusivity and high thermal inertia and hence, they can be also categorized as good thermal mass materials. However, from the structural point of view, LAFC can be only used in the low-rise building and normal housing application. In this regard, the finishing cost of LAFC can be little higher as compared to normal strength concrete.

3.8. SEM analysis

Microstructure of concrete is an important factor which affects its mechanical, thermal and hygroscopic properties to a large extent. Microstructure of LAFC mixtures were studied with the SEM analysis and results are shown in the Fig. 14. The effect of foam volume, SF and density (volume of ECA) on the microstructure of LAFC was analyzed. The influence of SF on the development of hydration products is shown in the Fig. 14a and b. Morphology of hydration products in the Fig. 14a indicates that LAFC mixture without SF contained high amount of calcium hydroxide (C–H). Moreover, needle shaped hydration products were also observed which exhibit the formation of ettringite. However, amount of C–H was considerably reduced in the LAFC containing SF (Fig. 14b). It could be due to intermingling of C–H and active SiO_2 from SF to form the extra C-S-H gel, which can further improve the mechanical properties of LAFC [6,53]. Fig. 14c and d shows the microstructure of lightweight concrete without and with 25% foam volume. The Fig. 14c shows that the microstructure of concrete mixture without foam showed highly denser structure as compared to the microstructure of LAFC mixture with 25% volume of foam (Fig. 14d) and volume of air-voids was increased in the mixture containing 25% foam volume. Hence, addition of foam played important role to modify the microstructure of concrete mixtures by increasing the air-voids, which can help to improve the hygrothermal properties of LAFC. Effect of SF on the microstructure of LAFC mixture is shown in the Fig. 14e and f. It can be observed that incorporation of SF had significant influence on microstructure of LAFC. Volume of air-voids was considerably reduced with the inclusion of SF, which can be associated with the physical and chemical effect of SF as discussed in Section 3.2. The effect of volume of ECA (density) on the microstructure of LAFC is shown in the Fig. 14g–j. Volume of ECA is inversely related to the density of LAFC mixtures. It can be observed from the microstructure of LAFC mixtures that, volume of air-voids was gradually reduced with the decrease in the volume of ECA from 49.4% to 20.1%, which was obviously due to higher amount of cement paste in high density LAFC mixtures (1000, 1200 and 1300 kg/m^3) as compared to 800 kg/m^3. Hence, LAFC mixtures with higher volume of ECA exhibited more porous structure, as porosity of ECA is considerably higher as compared to cement paste.

4. Conclusions

This study focused on the formulation of thermal insulating and structural lightweight aggregate foamed concrete to cut the energy requirement and promote sustainable development. LAFC mixture with four different densities (800, 1000, 1200 and 1300 kg/m^3) were prepared with the 0, 5 and 10% SF. Combination of stable foam and ECA was used to prepare the concrete with the self-flowing properties. Finally, LAFC mixtures were classified into different functional classes based on the results of mechanical, sorption and thermal properties. The following conclusions are drawn from the experimental findings.

1. Addition of stable foam was very helpful to avoid the segregation of ECA from the matrix. In accordance with ASTM C1611/C1611M, visual stability index of all LAFC mixtures was 0 and hence, all LAFC mixtures were regarded as high stable mixture in term of flow properties.
2. Mechanical properties of LAFC were improved with the increase in density from 800 to 1300 kg/m^3. Compressive strength and tensile strength of LAFC mixture 800-0SF were 6.50 MPa and 0.52 MPa which were increased to 24.30 MPa and 1.63 MPa for LAFC mixture 1300-10SF. Incorporation of SF also increased the compressive and tensile strength of LAFC mixtures.
3. Hygroscopic properties of LAFC mixtures were largely dependent on the density and dosage of SF. Sorptivity and water absorption of LAFC mixtures was reduced from 2.56 to 1.46 $kg/m^{-2}\ min^{-0.5}$ and from 23.8 to 6.8 vol% respectively, when density was increased from 800 to 1300 kg/m^3. Whereas, porosity of LAFC mixtures was declined to 35.32% from 70.63% with the decrease in the volume of ECA from 50% to 20%. Incorporation of SF also declined the sorption characteristics of LAFC.
4. Thermal properties of LAFC mixtures had a direct relationship with the increased in density and addition of SF. Thermal conductivity, volumetric specific heat capacity, thermal resistivity and thermal diffusivity of LAFC mixtures were in the range of 0.23–0.45 $Wm^{-1}\ K^{-1}$, 1136–1631 $kJ/m^3.K$, 518–261.5 °C.cm/W and 0.20–0.275 mm^2/s respectively, with the change in density of LAFC from 800 to 1300 kg/m^3.
5. SEM analysis showed that air-voids inside the LAFC mixtures were significantly decreased with the decrease in the volume of ECA and addition of SF. Results of permeable porosity test were also supported by the evidence of SEM analysis.
6. Finally, LAFC concrete mixtures were categorized into Class-I, Class-II and Class-III grade concrete based on their mechanical and thermal properties according to RILEM specification of lightweight concrete. Use of ECA volume in the range of 20–35% and foam volume of 25% can produce the structural grade

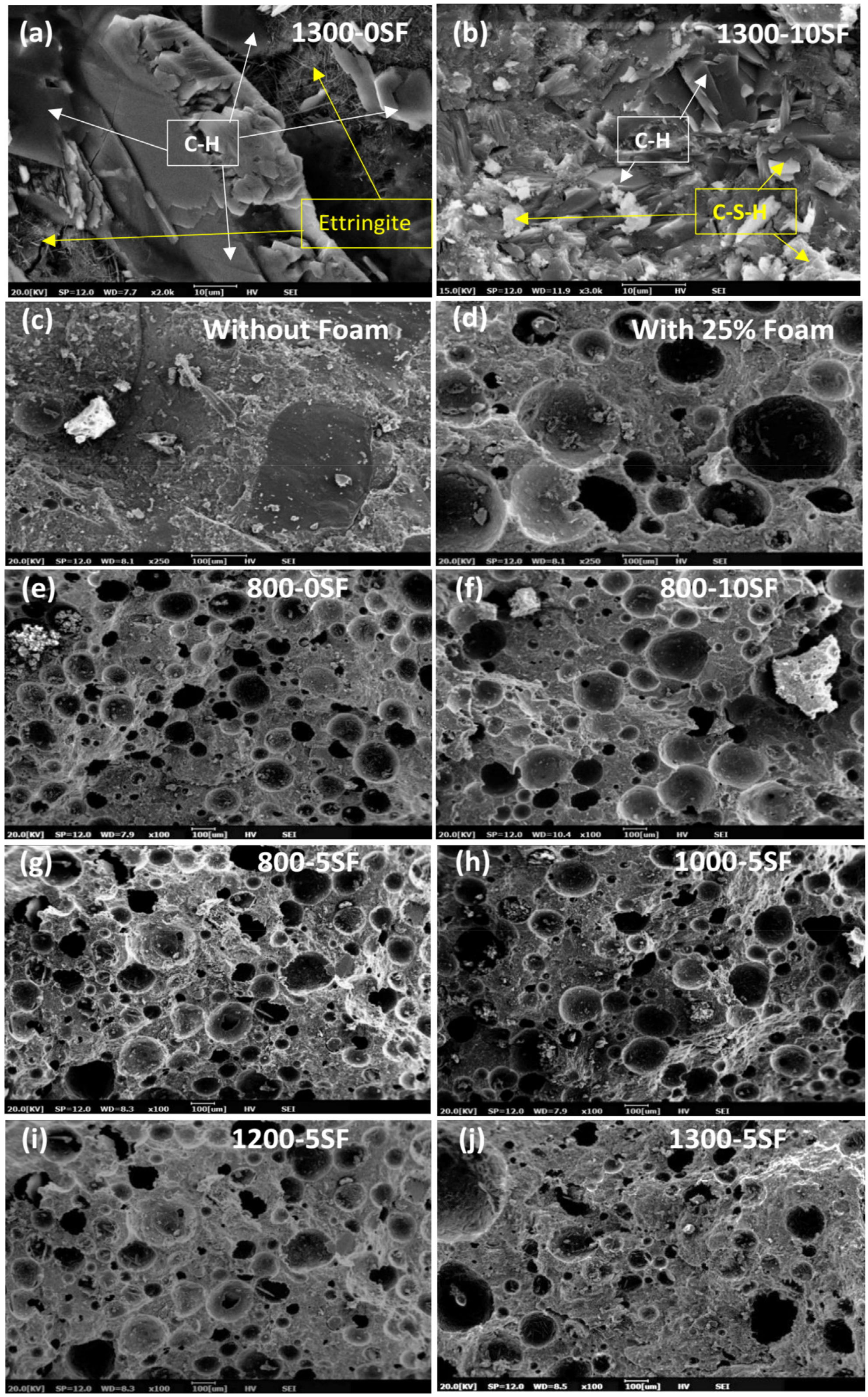

Fig. 14. Effect of foam, SF and ECA aggregate on the microstructure of concrete (a & b) hydration products in 1300-0SF and 1300-10SF (c & d) concrete mixtures without and with 25% foam (e & f) LFC mixtures without SF and with 10%SF (g–j) LFC mixtures with densities from 800 to 1300 kg/m^3 containing SF.

concrete (15–25 MPa). Whereas, thermal insulation grade concrete can be prepared with the ECA volume of 50% and foam volume of 25%.

Declaration of Competing Interest

None.

Acknowledgment

This research work was financially supported by the National Natural Science Foundation of China, Grant No. 51778363.

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