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Preliminary Investigation of Thermal Behavior of Lightweight Foamed Concrete Incorporating Palm Oil Fuel Ash and Eggshell Powder

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Abstract

This study was performed to investigate the thermal and mechanical properties of foamed concrete when supplementary cementitious materials (SCMs) are utilized. Sustainable foamed concrete of 1800 kg/m^3 dry density was prepared by incorporating Palm Oil Fuel Ash (POFA) ranging from 30 % to 35 % and Eggshell Powder (ESP) from 5 % to 15 % as SCMs. It was found that the combined utilization of POFA and ESP in the foamed concrete produced favorable results by reducing the thermal conductivity up to 42.68 % compared to the control sample, thus enhanced thermal insulating property of foamed concrete. This study confirmed that recycling and reusing of POFA and ESP are possible in foamed concrete which could be used for non-structural applications where thermal insulating is required.

Keywords

alternative building material, supplementary cementitious material, sustainable concrete, thermal insulating, Urban Heat Island (UHI)

1 Introduction

Concrete is an artificial building material which has revolutionized the way, human beings have been building the structures. Due to its flexibility and durability, its popularity has kept on increasing over the years [1]. It is a composite whose ingredients are cement, aggregates, and water [2]. Its long life, fire-resistance and low maintenance are the reasons that have increased the use all over the world. But one of the main problems that concrete has, is its low strength-to-weight ratio. Normal weight concrete's density varies from 2200 to 2600 kg/cm^3 [3], and this high density adds self-weight to the structure. However, reduction in density of concrete could be an economical solution for construction and could also help in reducing the cost of transportation, handling, and constructability. One way to make concrete reduce its self-weight is to make it lighter by introducing light-weight aggregates and foaming agent. Light-weight concrete is an innovative concrete in which a foaming agent is used to introduce air bubbles in such a way that the volume of the mixture is increased. This introduction of air bubbles significantly reduces self-weight, which can make it up to 87 % lighter as compared to the normal weight concrete and its density typically ranges from 300 to 1840 kg/cm^3 [4].

Foamed concrete is an innovative concrete which can be produced on construction site by mixing cement, sand, water and a stable foaming agent. Due to its reduced self-weight, excellent thermal insulation and self-compacting and levelling nature, foamed concrete has attracted many in the construction industry for various applications. With the ever-growing focus towards improving the sustainability of buildings, the demand for light-weight materials has increased, allowing foam concrete to present itself as a suitable as well as reliable material for sustainability. Many countries have started utilizing foamed concrete in the development and of precast blocks in construction [5]. Besides having low density, foamed concrete over the years

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has shown excellent performance in thermal and acoustic insulation. Depending upon the density of foamed concrete (400 to 1800 kg/m^3), the thermal conductivity can range between 0.10 to 0.82 W/mK. Previous studies have observed that foamed concrete of density from 1000 kg/m^3 to 1200 kg/m^3 achieved conductivity between 0.23 and 0.42 [6], while for 1400 kg/m^3 to 1800 kg/m^3, the thermal conductivity ranged from 0.66 to 0.82 W/mK [7, 8].

With the gradual increase in temperature across the world due to the global warming and urban heat island (UHI) effect, the utilization of foamed concrete panels as a thermal insulating element in the building is not only an innovative concept but also relevant. The UHI is a phenomenon observed in metropolitan areas, where the average urban temperatures are slightly warmer than adjacent rural areas [8]. The high thermal energy of the buildings and paving materials is the main factor for the development of UHI in metropolitan cities nowadays, which subsequently increases near-surface temperatures because of their increased thermal energy content. The ambient temperature in the cities is approximately 2 °C hotter than the surrounding rural areas. Meanwhile, in the highly densely populated areas are warmer up to 7 °C than their adjacent rural areas [9]. This rise in temperature can occur during the daytime as well as in the night-time. During the daytime concrete (walls and roof slabs) and asphalt will absorb solar energy while at night-time release the heat. Hence, it causes the temperature difference between urban cities and its surrounding rural area [10].

The high density of normal weight concrete indirectly increases the permanent load of the building in the form of self-weight as well as its thermal conductivity. The thermal conductivity of 2240 kg/m^3 has been reported to be 1.3 W/mK [11]. Being thermal conducive, the concrete surfaces absorb heat from the sun in the form of solar radiation instead of reflecting it, which causes the surface temperatures and ambient temperatures to increase. Malaysia, a tropical country that lies on the equatorial region, receives more heat as its climate remains mostly warm and humid throughout the year. According to the previous research [12], the intensity of UHI in Kuala Lumpur is varied from 3.9 to 5.5 °C. This UHI effect is influenced by the concentrations of infrastructures that are built using concrete and its tendency to absorb heat; Fig. 1 illustrates the absorption of heat from solar radiation.

Apart from this, concrete is known to have a carbon footprint, due to its main ingredient cement. With the rapid urbanization, the demand for cement has been on the rise. But during the production of cement, the cement industry releases CO_2 emissions which account to 7 % of

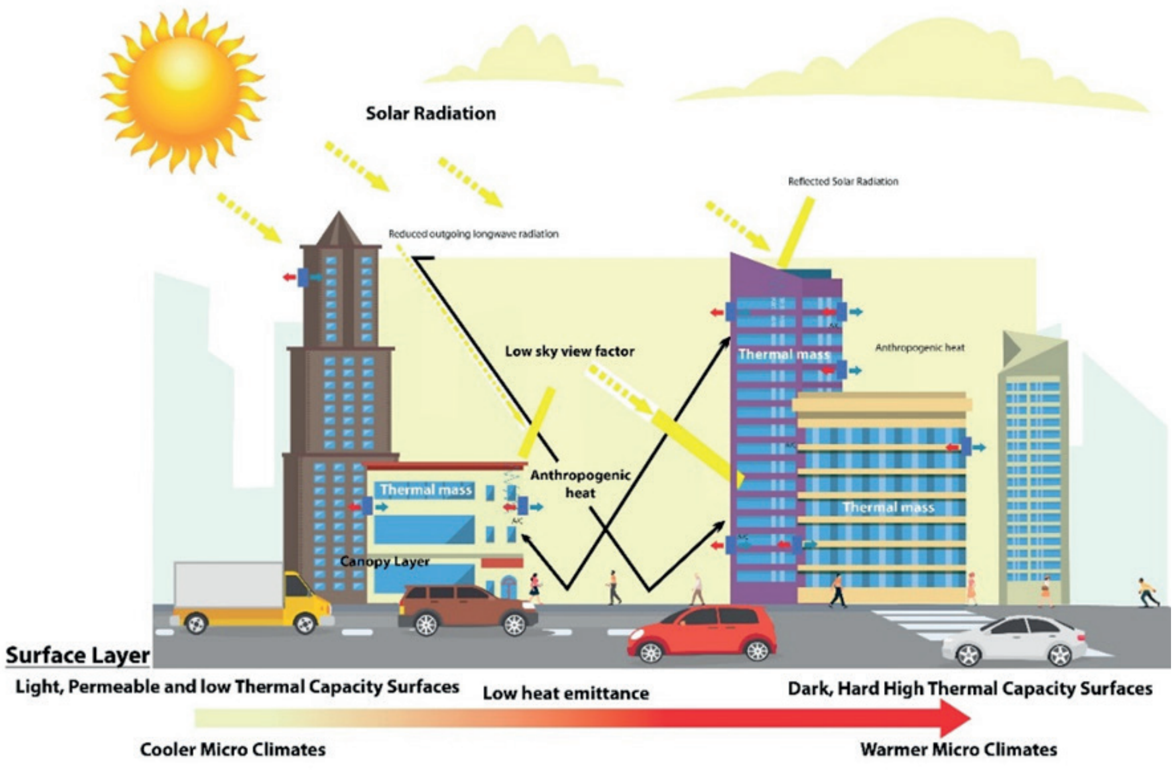

Fig. 1 Illustration of the UHI effect in an urban area [13]

the global CO_2 emissions [14]. Nowadays, to reduce the dependency of cement, researchers have focused eco-friendly concrete by utilizing supplementary cementitious materials (SCMs) especially waste by-products as partial replacement of cement [15]. The utilization of agricultural wastes as cement replacement is an innovative way to reduce the production of cement as well as produce green and sustainable concrete. With the rapid urbanization and industrialization, the generation of waste materials has increased significantly, and the disposal of such waste has become an environmental catastrophe. Malaysia is one of the largest palm oil producer, and exporter in the world, generates approximately 4 million tonnes of a waste product known as Palm Oil Fuel Ash (POFA) annually [16, 17]. This hazardous material is usually sent to be disposed at landfills without any commercial gains.

Another, major waste which is produced in large quantity is eggshells. In 2014, 10.65 billion eggs were consumed in Malaysia according to Malaysia Veterinary Department [18] and estimated to increase over the years with an increase of 400 million per year. Eggs are a cheap source of nutrition and eggshells are the waste product of eggs which ultimately end up in landfills without proper treatment, causing significant environmental pollution. With continuous disposal of waste materials, Malaysia is facing severe environmental issue regarding landfilling. The number of landfills has increased exponentially from 49 in 1998 to 161 in just 4 years [19]. By reducing the density of concrete, it will become economical construction and can solve the self-weight and the high heat transfer problems. The foamed concrete is an ideal solution for these limitations of normal weight concrete, and with the utilization of agricultural wastes such as POFA and Eggshell Powder (ESP) as partial cement replacement a sustainable foamed concrete can be developed. POFA has been used as an additive in foamed concrete of 1000 kg/m3 density; it has shown that it reduces the thermal conductivity slightly as compared to the controlled specimen [20]. Incorporation of POFA and ESP in sustainable foamed concrete will not only partially replace the cement content but also have thermal insulation properties which is the need of the hour in urban cities due to UHI effect.

This experimental work aimed at investigating the effect on the thermal behavior, in terms of surface temperature and thermal conductivity, of 1800 kg/m^3 dry density sustainable foamed concrete when POFA and ESP are incorporated as (SCMs).

2 Research methodology

2.1 Materials

This study considered 2:1 sand-cement to develop foamed concrete, with a stable foam of 1:20 (foaming agent to water) ratio. The Ordinary Portland Cement (OPC) used was ASTM Type 1 which adheres to MS 522 standards, while the sand was passed through 4.75 mm sieve. POFA was collected from nearby palm oil mill, while the eggshells were collected from local restaurants and bakeries in the vicinity. The fineness of cement influences the strength of concrete [21] and since waste materials such as POFA and ESP are being used as a cement replacement, both waste materials need to have adequate fineness [22]. Therefore, POFA was first sieved using 300 μm in order to remove any impurities and then oven-dried for 24 hours at a constant temperature of 105 ± 5 °C. Afterwards, the oven-dried POFA was grounded into fine particles using the Los Angeles Abrasion Machine. After the grinding process, the POFA was once again sieved through 150 μm.

The collected eggshells contained whitish and yellowish fluid, which may be the membrane, albumen, or the yolk of the egg; this is an excessive fluid which is not required. Therefore, to remove this unnecessary fluid, the collected eggshells were immediately washed thoroughly with clean and potable water and then left to open-air to dry the water. Afterwards the eggshells oven-dried for 24 hours at a constant temperature of 105 ± 5 °C. After the moisture is removed from the eggshells during oven-dry, the eggshells become crispy, allowing it to be crushed into small particles. The crushed eggshells were then put into Los Angeles Abrasion machine for grinding process. After the grinding process, the ground eggshells were sieved through 75 μm. The eggshells which were retained on 75 μm sieve were crushed again until it passed 75 μm. Additionally, a small blender was also used to ground the retaining eggshell into powdery ash which gives through 75 μm. It has been found that grinding waste materials is an effective way to turn these large particles into small size and homogenous powder like cement and increase the mechano-chemical activation.

2.2 Properties of binders

The chemical and physical properties of the binders (OPC, POFA and ESP) was determined. From Fig. 2, it can be observed that both POFA and ESP have been grounded properly and achieve quite similar particle size distribution curve to that of OPC. The physical properties of

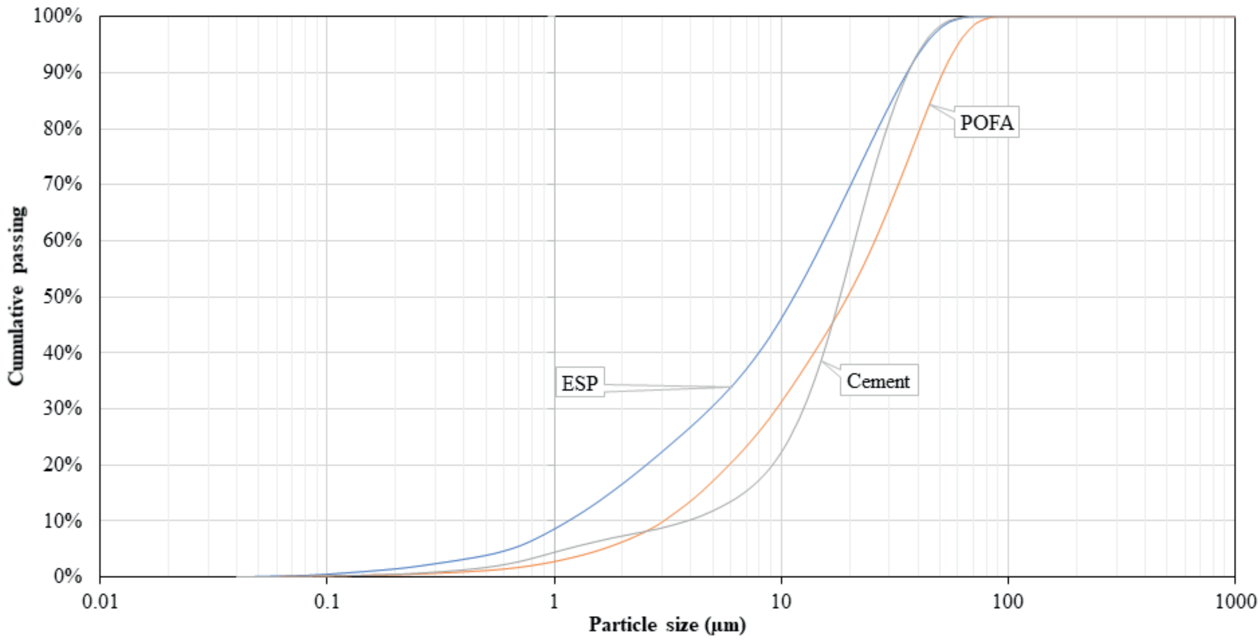

Fig. 2 Particle size distribution of binders [24]

binders are tabulated in Table 1. As observed in Table 1, the specific surface area of POFA was close to OPC; however, the specific surface area of ESP was more than double of OPC. This could be attributed to the porosity of ground ESP and continuous grinding.

The chemical composition of the binders was determined using X-Ray Fluorescence (XRF) which is shown in Table 2. Based upon the classifications provided in the ASTM C618-19 [23], the POFA used in this study can be categorized as Class-C pozzolanic as the sum of SiO_2 + Al_2O_3 + Fe_2O_3 of POFA is approximately 61.75 % [24].

Table 1 Physical properties of binder materials [24]

Physical Properties	OPC	POFA	ESP
% Passing through 45 μm (no. 325) sieve	96.47	84.23	95.95
Median Particle Size, d50 (μm)	18.4	19.6	11.4
Specific Surface Area (cm^2/g)	4870.81	4532.38	9740.14
Specific Gravity	3.14	2.12	2.34

Table 2 Chemical composition of binder materials [24]

Chemical Composition	OPC	POFA	ESP
Calcium Oxide (CaO)	63.95%	8.10%	88.76%
Silica dioxide (SiO_2)	20.61%	51.83%	1.63%
Aluminium Oxide (Al_2O_3)	3.95%	2.32%	-
Iron oxide (Fe_2O_3)	3.46%	7.60%	0.05%
Magnesium oxide (MgO)	1.93%	3.13%	0.91%
Potassium oxide (K_2O)	-	13.72%	0.24%
Carbon (C)	-	0.28%	-
Sulphur oxide (SO_3)	3.62%	2.23%	0.81%
Phosphorus pentoxide (P_2O_5)	-	4.30%	-
LOI	2.18	6.29	7.6

2.3 Experimental procedure

In this experimental investigation, the sustainable foamed concrete was cast based on the target wet density of 1900 kg/m^3. The control foamed concrete specimen was cast for comparison. The amounts of 30 % and 35 % POFA was used to replace cement while ESP content was varied from 5 % to 15 % by weight, as shown in Table 3. The preparation of Foamed concrete is a three-phase procedure:

1. *slurry preparation* – The slurry was prepared by mixing dry binder materials for the specific mix batch and sand in the rotary concrete mixer and left to mix for 3 minutes so that the binders and sand are mixed thoroughly. Afterwards, the measured water as per the w/b ratio was gradually added and left to mix for another 5 minutes. The water-binder ratio was taken as 0.55 and sand-cement ratio as 2:1 for this study, as shown in Table 3.
2. *foam preparation* – Foaming agent (Sika AER 50/50), water and a foam generator were used to prepare the foam. In the foam generator, the ratio of 1:20 of a foaming agent to water was applied to produce foam, which was then gradually added in the mixer to reduce the wet density and so that the target density could be achieved. The air pressure in the foam generator was sustained between 60 and 80 kPa.

Table 3 Mix Proportions and amount of materials required for 1m^3 foamed concrete

Mix	% of Binder Content			Amount of Quantities (kg)					Quantities Required to Produce Foam (litres)		
	Cement	POFA	ESP	Cement	POFA	ESP	Sand	Water	Foaming Agent	Water	Foam Required in the mix
S0	100	0	0	535.21	0	0	1070.42	294.37	0.30	6.06	125.06
S1	65	30	5	347.89	160.56	26.76	1070.42	294.37	0.30	6.06	125.06
S2	60	30	10	321.13	160.56	53.52	1070.42	294.37	0.30	6.06	125.06
S3	55	30	15	294.37	160.56	80.28	1070.42	294.37	0.30	6.06	125.06
S4	60	35	5	321.13	187.32	26.76	1070.42	294.37	0.30	6.06	125.06
S5	55	35	10	294.37	187.32	53.52	1070.42	294.37	0.30	6.06	125.06
S6	50	35	15	267.61	187.32	80.28	1070.42	294.37	0.30	6.06	125.06

3. *mixing of slurry and foam* – Before adding the foam, the density of the wet slurry was determined to be 2104.2 kg/m^3, using density bottle. Once the density of non-foam wet mix was measured, the pre-generated foam was added gradually to achieve the wet target density of 1900 kg/m^3, the density of the wet mix was measured after each time foam was added.

The sustainable foamed concrete was then poured into the beforehand-prepared moulds and kept for 24 hours. Afterwards, the specimens were demoulded and kept for air-curing at ambient temperature for a specified period.

This study aims to evaluate the thermal insulating performance of foamed concrete incorporating POFA and ESP as SCMs. For each mix batch, a total of three (03) panels of 300 × 300 × 50 mm dimension were prepared. Thermal conductivity can be considered as the property of any material to conduct heat and is evaluated in terms of the Fourier's Law for heat conduction [25, 26]. The material's ability to transfer heat through it, is known as the thermal conductivity [7]. The thermal conductivity test set-up is based on BS EN12664:2001 [27]. The foamed concrete sample was placed between hot and cold plates in the thermal conductivity test machine. The thermocouples and wiring attached are connected to a data logger and a multiplexer. The temperatures of the hot and cold plate were configured before the test was started. The specimen panels achieved 28 days' air curing before the conduction of thermal conductivity test. Holes with various depths (10, 15, 20 and 30 mm) were drilled so that the thermocouples can be inserted [8]. Afterwards, the samples were placed in between the two plates. To replicate the thermal conditions which the concrete may face, the temperatures were set at 18 and 40 °C for the cold and hot plates, respectively. The hot and cold plates were covered with one layer of barrier cushion while cork sheet was insulated on all sides of the sample [28]. The temperatures of the plates were recorded at 30 minutes interval, and the testing continued for 24 hours for each sample.

Heat transfer is a dynamic process between the concrete and the surrounding, which involves conduction, convection, and radiation. Surface temperature tests are based on the theory that the change in material thermal properties, including those caused by subsurface defects, influence the heat transfer of any substance [29]. Since this experimental work aims to study the thermal performance of foamed concrete incorporating waste materials as a cement replacement, therefore, the surface temperature of specimens is necessary to evaluate the heat absorption and its effect on the surface of the specimen. The samples for thermal conductivity were first tested for surface temperature, which is a non-destructive test. For the measurement of the intensity of the solar radiation applied on the samples, *BABUC* pyranometer was used. While for measuring the ambient temperature *BABUC* globe was used. Both the ambient temperature and the solar radiation were recorded using *BABUC* data logger shown in Fig. 3.

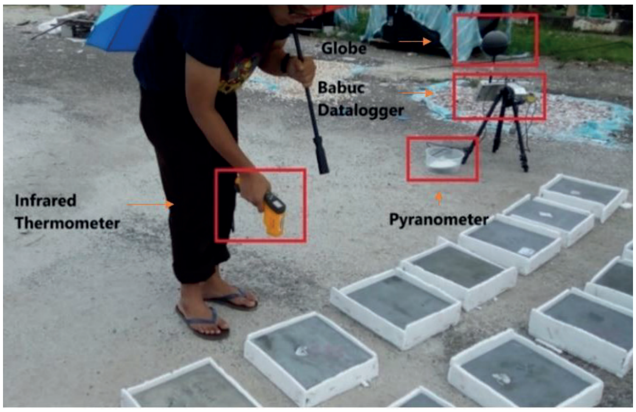

Fig. 3 Surface temperature setup

The surface temperature of non-metallic surfaces such as concrete, was measured using infrared thermometer [30]. The main use of thermometers is to determine the surface temperature of any object by measuring the amount of infrared energy being radiated by the object's surface, as shown in Fig. 4. For measuring surface temperature, *FLUKE* handheld 66 IR thermometer was utilized who's operational range from -32 °C to 600 °C and distance-to-spot ratio of 30:1.

The Infrared thermometer was held at 30.48 cm high then the surface of the samples. The emissivity of the thermometer can be set from 0.1 to 1.00 depending upon the surface material, since the surface temperature was to be measured of concrete, for this study, the emissivity was set to 0.95. The surface temperature readings were recorded for three (3) consecutive days from 10:00 A.M. to 4:00 P.M. with an interval of 15 minutes. The following procedure used by the authors is a modification from Anting et al. [31]:

a) The samples were insulated on all side by using polystyrene except the top surface. The top surface of the specimen was left exposed so that the heat flow be in 1-dimensional.
b) The intensity of solar radiation was recorded. The surface temperature of 5 different points on the surface of the specimen was recorded using the infrared thermometer to get an average reading of the surface.
c) The mean surface temperature of the sample was calculated from the data.

To complement the analysis of the thermal behavior of light-weight foamed concrete, the mechanical properties in terms of compressive and splitting tensile strength of foamed concrete incorporating SCMs were evaluated in this study. Three (03) cube samples of 0.1 m dimension were prepared for each mix to be tested for compressive strength in accordance to BS EN 12390-3:2019 [33] at 7- and 28-days air curing, while three (03) cylindrical specimens of 200 mm × 100 mm were prepared for splitting tensile strength in accordance to BS EN 12390-6:2009 [34]. The mechanical properties have been published by the authors separately [24]; however, they are cited in this article for clarification of the thermal behavior of lightweight foamed concrete and discussed under mechanical properties section.

3 Results and discussion

3.1 Thermal conductivity

The difference between the maximum surface temperature of the control sample (S0) and the maximum surface temperature of samples containing POFA and ESP decreased with the increase in the ESP content. This heat transfer can be reduced with the use of foamed concrete. This is proven in this study, according to Table 4, the average thermal conductivity of the control sample of 1800 kg/m^3 density foamed concrete was determined to be 0.82 W/mK. This is due to the development of pore voids in the matrix of the foamed concrete.

The S1 sample achieved the lowest thermal conductivity value of 0.47 W/mK, which was approximately 42.68 % less than the control sample. With the increase in the content of ESP in the sustainable foamed concrete, the thermal conductivity values fluctuated. With further increase in POFA content (S4, S5 and S6 samples), the thermal conductivity value increased slightly. Based upon the results, the reduction in thermal conductivity of sustainable foamed concrete incorporating POFA and ESP as cement replacement can be attributed to the presence of more voids in the mortars, which was due to the delayed pozzolanic reaction of POFA. A previous study [35] has determined that the utilization of POFA can reduce the thermal conductivity value from 15 % to 50 %. From the

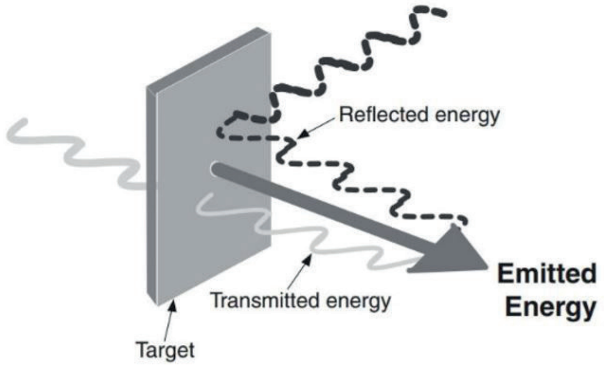

Fig. 4 Mechanism of Fluke 66 IR thermometer [32]

Table 4 Thermal conductivity of sustainable foamed concrete

Mix proportion	Thermal conductivity (W/mK)	Difference in thermal conductivity compared to the S0 Sample (%)
S0	0.82	---
S1	0.47	- 42.68
S2	0.65	- 20.73
S3	0.59	- 28.05
S4	0.62	- 24.39
S5	0.65	- 20.73
S6	0.60	- 26.83

results, the addition of POFA and ESP in foamed concrete as cement replacement can reduce the thermal conductivity from 20.73 % to 42.68 % compared to the control sample, which is in correlation with the previous finding. The variance in the reduction of thermal conductivity is due to the increase in POFA and ESP contents.

3.2 Surface temperature

Fig. 5 shows the surface temperature on all three consecutive days, from 10 A.M to 4:00 P.M. While the surface temperature results are summarized in Table 5. Based on the data, the surface temperature during the maximum sun intensity on day one was still not the maximum surface

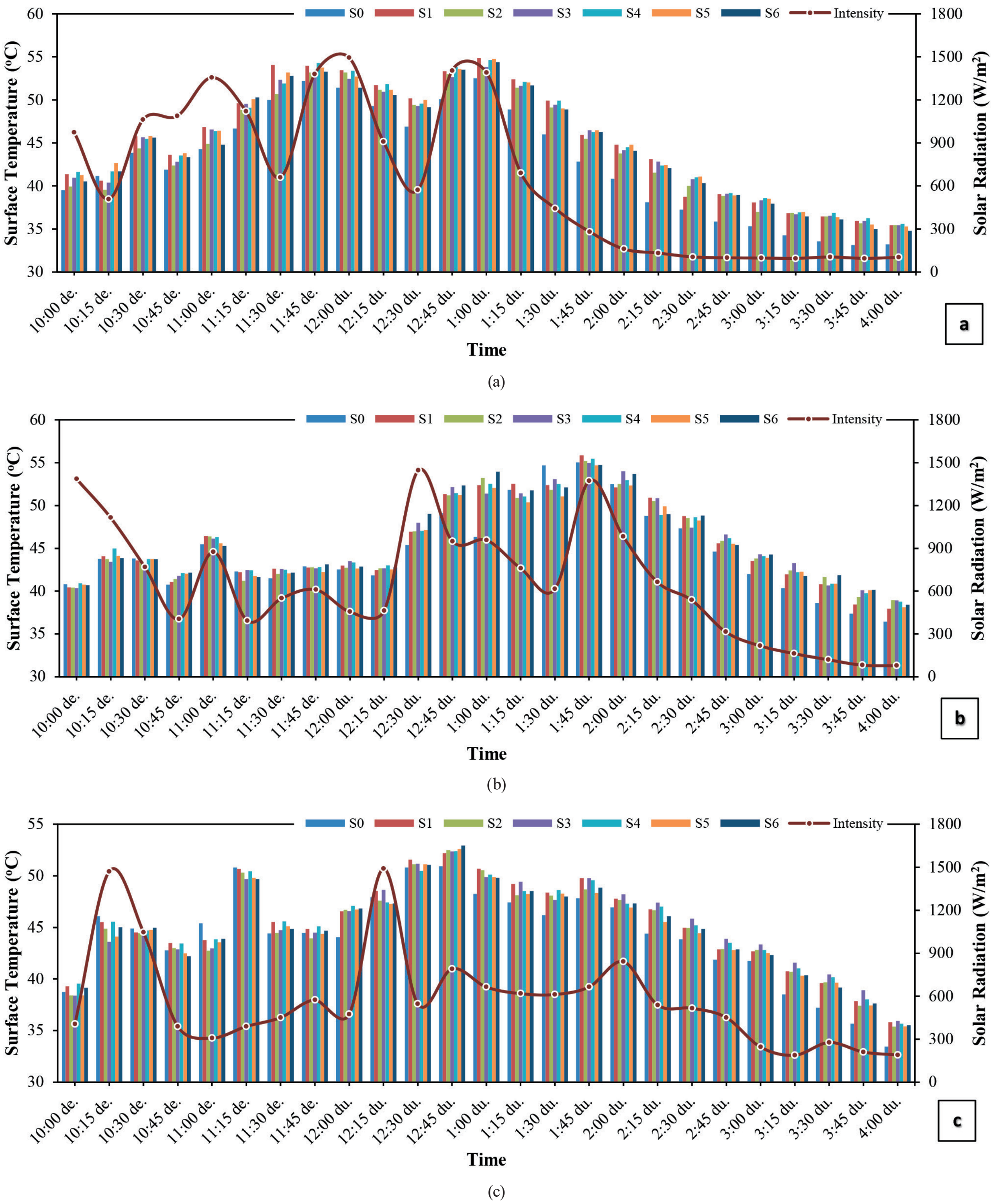

Fig. 5 Surface temperature readings on (a) Day 1 (b) Day 2 (c) Day 3

Table 5 Summary of surface temperature readings

Day	Mix	Maximum Intensity (W/m^2)	Max. solar radiation		Peak temperature		Difference	
			Time	Surface temp. (°C)	Time	Surface temp. (°C)	Surface temp. (°C)	Time difference (minutes)
Day One	S0	1495	12:00 P.M.	51.42	1:00 P.M.	52.52	+ 1.10	60
	S1			53.44		54.86	+ 1.42	
	S2			53.20		53.86	+ 0.66	
	S3			52.46		53.84	+ 1.38	
	S4			53.40		54.64	+ 1.24	
	S5			52.72		54.76	+ 2.04	
	S6			51.42		54.38	+ 2.96	
Day Two	S0	1446	12:30 P.M.	45.40	1:45 P.M.	52.04	+ 6.64	75
	S1			46.92		55.86	+ 8.94	
	S2			46.98		55.20	+ 8.02	
	S3			47.98		54.98	+ 7.00	
	S4			47.04		55.46	+ 8.42	
	S5			47.12		54.70	+ 7.58	
	S6			49.02		54.74	+ 5.72	
Day Three	S0	1490	12:15 P.M.	47.92	12:45 P.M.	50.94	+ 3.02	30
	S1			48.54		52.2	+ 3.66	
	S2			47.6		52.5	+ 4.90	
	S3			48.64		52.36	+ 3.72	
	S4			47.42		52.38	+ 4.96	
	S5			47.28		52.6	+ 5.32	
	S6			47.32		52.94	+ 5.62	

temperature that can be achieved. The maximum solar radiation was recorded to be 1495 W/m^2 at 12:00 P.M. The lowest surface temperature was recorded for S0 sample which was 51.42 °C at the event of maximum solar radiation, while the surface temperature for other samples containing POFA and ESP was slightly higher. After passing of 60 minutes, the peak surface temperature occurred, with control sample recording 52.52 °C while sample S1 recorded the highest temperature of 54.86 °C, which was 2.34 °C higher than the control sample. With the addition of ESP, the surface temperature slightly reduced. All other samples also recorded higher surface temperatures when the intensity of solar radiation was at maximum, and peak temperature of samples was 1.32 to 2.34 °C higher than S0.

On day two, the maximum solar radiation was recorded at 12:30 P.M. while the peak temperature was observed after 75 minutes. As compared to day one, the surface temperature recorded at the time of maximum radiation was slightly lower, but the peak temperature increased more. On day three, the maximum surface temperature was recorded at 12:15 P.M. while the peak temperature was recorded after 30 minutes. Surface temperatures of the samples had a similar trend as day 1 and day 2. The maximum solar radiations were recorded between 1446 to 1495 W/m^2 during three days of testing. It was observed that the maximum solar radiations occurred between 12:00 P.M. to 12:30 P.M. The surface temperature recorded at the occurrence of maximum solar radiation was by far not the maximum or peak surface temperature recorded by the samples. The maximum surface temperature was recorded 30 to 75 minutes after the occurrence of maximum solar radiation. The increase in surface temperature beyond the maximum solar radiations due to more radiations absorbed by the material, the radiation is transferred to materials atoms.

Eventually, this absorbed radiation is released by the material as heat, thus heating the surface of the material further. This process can vary in speed as well as intensity depending upon the material's properties. The control sample showed a relatively lower increase from the surface temperature recorded at maximum solar radiation to the maximum surface temperature recorded later, compared to other samples containing POFA and ESP. It was observed that addition of POFA content into the concrete as a cement replacement, POFA being blackish, turns the light grey color of sustainable foamed concrete into darker grey or blackish color.

A black surface will absorb all the solar radiation it receives having albedo of 0, while whiter surfaces will reflect this radiation having albedo of 1. Therefore, the effect of the addition of POFA in foamed concrete on the surface temperature or heat absorbed by the samples is visible. With the increase in POFA content, the surface temperature should increase, however, this is not the case as along with the increase in POFA content, the ESP (whitish) content is also increased; therefore it can be seen that even with high POFA content in the concrete specimens, those specimens do not necessarily obtain high surface temperature.

Except for day 2, the other days had overcast conditions at frequent intervals, though the intensity of radiation was recorded to be higher, the overcast conditions directly had an impact on the surface temperature. For day 2, fewer clouds were observed, even though the intensity of radiation was relatively less than the other days, the radiation was allowed to be directly applied on the surface of the samples for longer periods; therefore, the surface temperature readings were much higher than days 1 and 3.

3.3 Mechanical properties

Fig. 6 shows the average compressive strength of lightweight foamed concrete. It can be observed that the S0 sample of foamed concrete attained a compressive strength of 14.25 and 17.1 MPa at 7 and 28 days, respectively. All the mixes which incorporated POFA and ESP achieved reduced compressive strength ranging from 8.27 % to 43.16 % compared to S0 at 7 days. This reduction may be associated with the decrease in cement content, furthermore, though POFA is a known pozzolanic material; however, strength gain due to pozzolanic activity is rarely seen at the early stage. The result of the pozzolanic reaction and the combined POFA-ESP replacement can be observed from the compressive strength at 28 days. The strength gain ranged from 1.75 % to 12.57 %. Though increased replacement progressively decreases the compressive strength. The strength gain is attributed to increased pozzolanic activity [24].

POFA is well known pozzolanic material containing high content of SiO_2, when the pozzolanic material comes in contact with water, a reaction is triggered which starts to consume the $Ca(OH)_2$ to develop additional calcium-silicate-hydride (C-S-H) gels, which strengthen the concrete. POFA has been utilized as a partial cement substitute in concrete; however, it could only substitute a certain amount of cement, as, during the pozzolanic reaction, cement will only supply a small amount of free lime that POFA could absorb and produce C-S-H gels. Additional $Ca(OH)_2$ added with POFA during concrete manufacturing can increase POFA content. This theory is confirmed as ESP has additional CaO that POFA can absorb during the pozzolanic reaction and increase concrete POFA material [24]. The combined usage of POFA and ESP not only increases the POFA content that can be included in

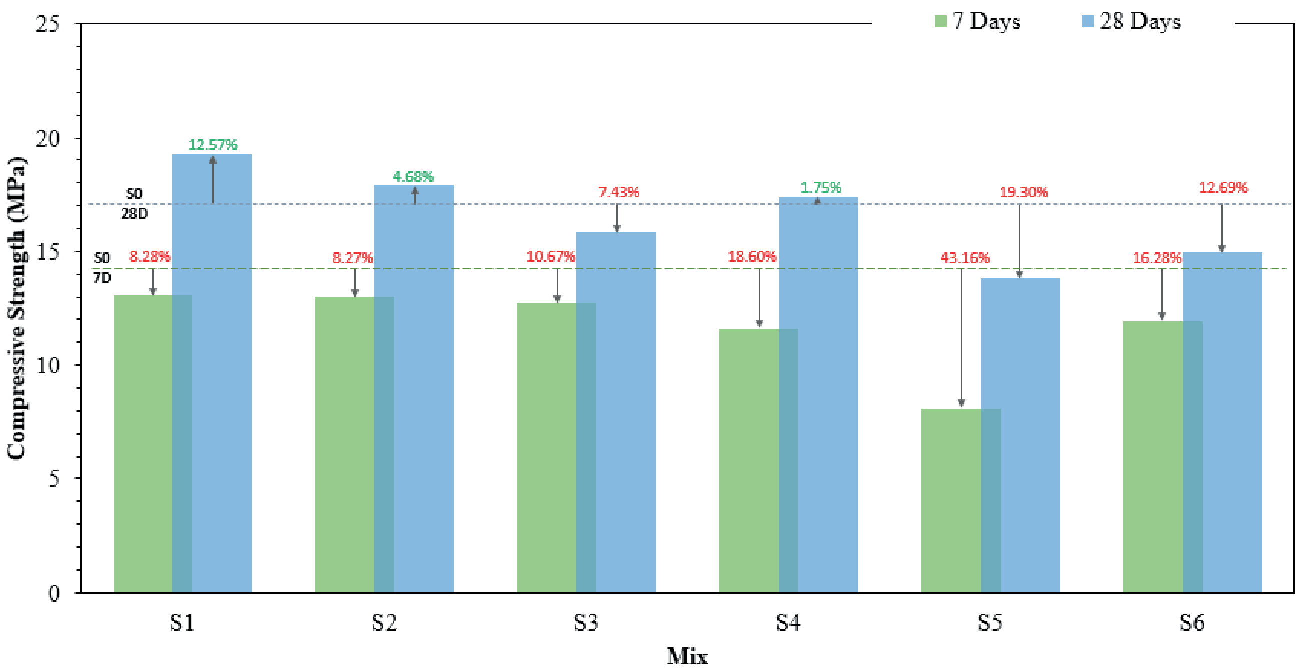

Fig. 6 Compressive strength of lightweight sustainable foamed concrete w.r.t control (S0) sample [24]

concrete but also increased the cement replacement content as 5–10 % ESP can also be used along with increased POFA content as cement substitute material, making a total of 40 % cement substitution without compromising the strength of concrete. The pattern found in this experimental study parallels previous studies [36, 37].

However, this increase in strength could not be seen in the splitting tensile testing of light-weight foamed concrete. From Fig. 7, the splitting tensile strength of the specimens are shown with a percentage indicating the decrease in strength with respect to the control sample (S0), which achieved 2.07 MPa splitting tensile strength at 28 days age. The tensile strength of foamed concrete comprising the SCMs is weaker than the control sample. The high content of SCMs in light-weight foamed concrete might not be successful in improving the interfacial transition zone between sand and binder matrix. By comparison, the joint usage of POFA and ESP comparatively enhanced the compressive strength; this enhancement is most definitely attributed to the increase in the foamed concrete binder matrix [24].

Based upon the compressive and tensile strength results, a linear relationship is developed. The R^2, which is calculated by the regression curve, is the co-efficient relationship in this experimental work. The regression curve line indicates the relationship in the graph between the independent variable (compressive strength) and the dependent variable (splitting tensile strength), as seen in Fig. 8(a), taking into account control (S0) sample results.

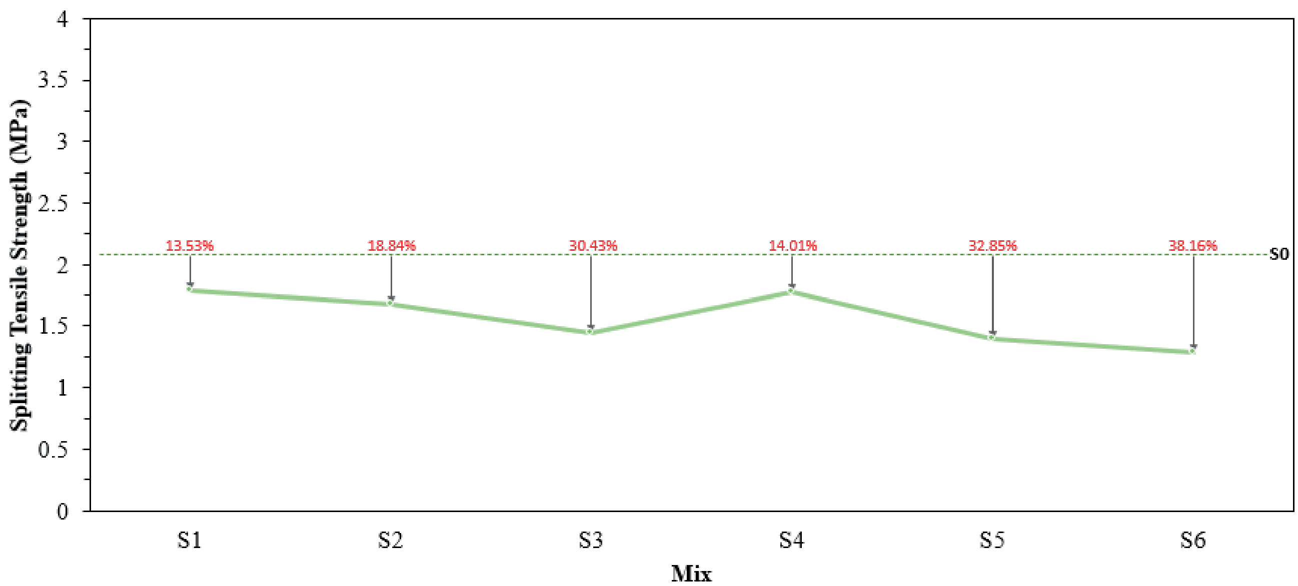

Fig. 7 Splitting tensile strength of lightweight sustainable foamed concrete w.r.t control (S0) sample [24]

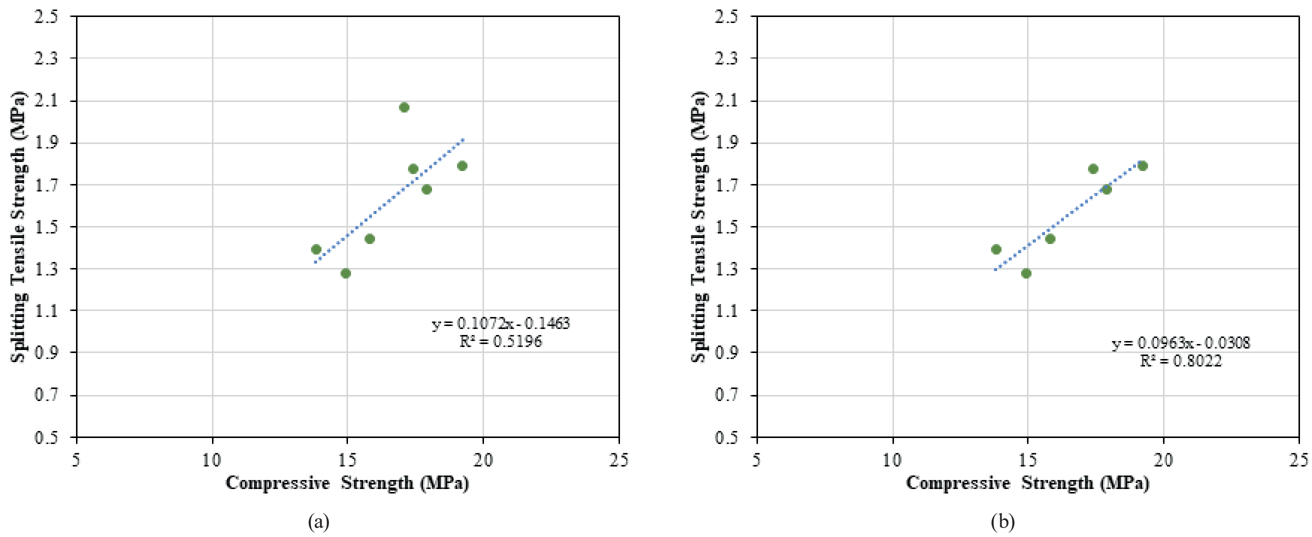

Fig. 8 Correlation between compressive-tensile strength of foamed concrete (a) all values (b) after removal of outlier samples

The equation formed with R^2 coefficients as given below:

$$f_t = 0.1072 f_{cu} - 0.1463 \quad R^2 = 0.5196 , \tag{1}$$

where:

f_{cu} = Compressive strength (MPa),

f_t = Splitting tensile strength (MPa).

It can be found that $R^2 = 0.5196$ is very bad correlation since there is one point that is outlier and does not correspond with the others. This is the reference set, which does not include any SCM. However, if the association excludes this outlier value, a new corelation can be formed as seen in Fig. 8(b). R^2 is slightly increased to 0.8022, indicating that studies of cement substitution have strong association. Thus, the findings obtained in these series appear to indicate a significant pattern, but they do not agree with foamed concrete without cement substitution. The developed equation, along with the R^2 coefficients as provided below:

$$f_t = 0.0963 f_{cu} - 0.0308 \quad R^2 = 0.8022 . \tag{2}$$

4 Conclusions

In this experimental study, an innovative thermally insulating sustainable foamed concrete incorporating supplementary cementitious materials, palm oil fuel ash and eggshell powder, was evaluated in terms of its thermal and mechanical properties to determine its potential utilization in urban areas. It was observed that POFA and ESP are compatible with cementitious resources since POFA being pozzolanic material requires CaO to consume and produce C-S-H gels. The additional CaO can be provided with the addition of ESP. The partial supplement of cement will help in reducing the production of cement and ultimately reduce the emission of CO_2. At the same time, also contribute towards the reduction of ESP and POFA's negative impact on the environment and provide a beneficial means instead of disposing of in landfills.

It was observed that the samples containing POFA and ESP absorbed more heat than the control sample due to the albedo effect. However, sample S1 recorded the highest surface temperature of 54.86 °C. The temperature reduced on the surface of the samples when the ESP content was added. With the addition of ESP content, the surface temperature slightly reduces. Though due to varied intensity of solar radiation and overcast conditions the surface temperatures of sample varied. The cement replacement in sustainable foamed concrete by using POFA and ESP also helped in reducing the thermal conductivity up to 42.68 % compared to the control sample. Higher the cement replacement, the less reduction in thermal conductivity value can be seen. Furthermore, 35–40 % cement content replacement by POFA and ESP achieved slightly higher compressive strength.

Based upon the results determined, it was observed that the combined utilization of POFA and ESP further reduced the thermal conductivity of foamed concrete allowing it to exhibit enhanced thermal insulation and could be used for non-structural applications. The combined use of POFA and ESP not only helped in develop eco-friendly concrete with significantly reduced cement content but also minimizes the use of natural resources. Furthermore, by utilizing the waste materials as supplementary cementitious materials in such a way contributes to the reduction in disposal of agro-industrial waste materials in landfills and reducing the environmental issues associated with the landfilling.

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