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RESEARCH ARTICLE

Thermo-mechanical properties and sustainability analysis of newly developed eco-friendly structural foamed concrete by reusing palm oil fuel ash and eggshell powder as supplementary cementitious materials

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Abstract

The production of cement contributes to 10% of global carbon dioxide (CO_2) pollution and 74 to 81% towards the total CO_2 pollution by concrete. In addition to that, its low strength-to-weight ratio, high density and thermal conductivity are among the few limitations of heavy weight concrete. Therefore, this study was carried out to provide a solution to these limitations by developing innovative eco-friendly lightweight foamed concrete (LFC) of 1800 kg/m^3 density incorporating 20–25% palm oil fuel ash (POFA) and 5–15% eggshell powder (ESP) by weight of total binder as supplementary cementitious material (SCM). The influence of combined utilization of POFA and ESP on the fresh state properties of eco-friendly LFC was determined using the J-ring test. To determine the mechanical properties, a total of 48 cubes and 24 cylinders were prepared for compressive strength, splitting tensile strength and modulus of elasticity each. A total of 24 panels were prepared to determine the thermal properties in terms of surface temperature and thermal conductivity. Furthermore, to assess the environmental impact and eco-friendliness of the developed LFC, the embodied carbon and eco-strength efficiency was calculated. It was determined that the utilization of POFA and ESP reduced the workability slightly but enhanced the mechanical properties of LFC (17.05 to 22.60 MPa compressive strength and 1.43 to 2.61 MPa tensile strength), thus satisfies the ACI213R requirements for structural lightweight concrete and that it can be used for structural applications. Additionally, the thermal conductivity reduced ranging from 0.55 to 0.63 W/mK compared to 0.82 W/mK achieved by control sample. Furthermore, the developed LFC showed a 16.96 to 33.55% reduction in embodied carbon and exhibited higher eco-strength efficiency between 47.82 and 76.97%. Overall, the combined utilization of POFA and ESP as SCMs not only enhanced the thermo-mechanical performance, makes the sustainable LFC as structural lightweight concrete, but also has reduced the environmental impacts caused by the disposal of POFA and ESP in landfills as well as reducing the total CO_2 emissions during the production of eco-friendly LFC.

Keywords Eco-strength efficiency · eggshell powder · palm oil fuel ash · supplementary cementitious materials · surface temperature · thermal conductivity

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Introduction

Concrete has revolutionized the way human beings construct the buildings. Despite its success and being the most used construction material, it has some drawbacks, including its poor strength-to-weight ratio. Heavy weight concrete has significantly high density (2200 to 2600 kg/m^3) (Rafi et al. 2014), which places additional permanent load on structural components. Owing to its high density, heavy weight concrete implicitly raises the building's thermal stresses, creating thermal discomfort among dwellers. The thermal conductivity of 2240 kg/m^3 density heavy weight concrete was 1.3 W/mK (Soebarto 2009). The disadvantage of being thermal conducive or having higher thermal conductivity is that instead of reflecting the solar radiation, it absorbs and allows the heat to transfer through the concrete matrix. Tropical countries like Malaysia, in the equatorial region, receive more heat as the atmosphere stays largely warm and humid during the year. The urban heat island (UHI) effect is a phenomenon that occurs mainly in urban areas where average temperatures are marginally higher than areas that surround it (Akbari et al. 2008) as seen in Fig. 1, allowing virtual 'heat islands' to develop. The concentration of infrastructures constructed using concrete and asphalt and their ability to absorb heat influence as well as facilitate the UHI effect (Ibrahim et al. 2018). The engineered materials such as concrete and asphalt have higher heat storage capacity and lower albedo (Golden and Kaloush 2006; Mohajerani et al. 2017) and are nowadays the key driver for UHI, which consequently raises the average urban temperatures due to their elevated thermal energy content. The cities' ambient temperature is around 2°C warmer than rural surroundings. Meanwhile, heavily inhabited regions are warmed up to 7°C compared to the surrounding areas (Shahmohamadi et al. 2011). This temperature increase could occur anytime during the day or even at night. It triggers the temperature differential between metropolitan cities and their rural surroundings (Bristow et al. 2010).

Lightweight foamed concrete (LFC) is an innovative type of lightweight concrete which utilizes a foaming agent to add air bubbles to raise the mixture's volume, thus greatly decreasing the self-weight. The air bubbles in the LFC reduce the concrete's thermal mass, which worsens the heat storage capacity of the LFC (Kumar et al. 2020). The LFC can be made up to 87% lighter than heavy weight concrete, and its density usually varies from 300 to 1840 kg/m^3 (Mohamad et al. 2015) due to the absence of coarse aggregates. LFC is commonly used in the building industry in numerous applications, as seen in Table 1 (Mohd Sari and Mohammed Sani 2017; Jhatial et al. 2020b), owing to its wide variety of benefits. Reducing LFC density will result in lower thermal conductivity values, as seen in Fig. 2. With the ever-growing emphasis on building sustainability, demand for lightweight materials has increased, allowing LFC to portrait itself as a viable and sustainable material. Recently, several countries have started using LFC in building construction and precast blocks due to technological, economic and environmental benefits (Jones et al. 2016). Besides reaching lower density, LFC has outstanding thermal and acoustic insulating properties. The notion of LFC being utilized as a thermal insulating building element is not just a revolutionary idea but also important with the increase in climate change and UHI.

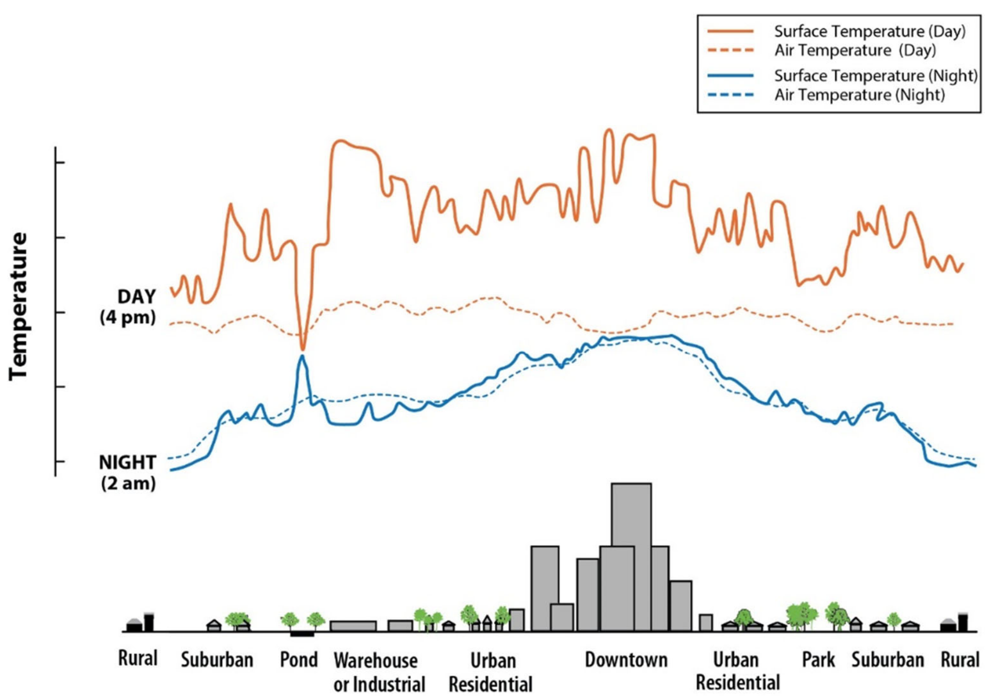


Fig. 1 Urban heat island (Akbari et al. 2008)

Table 1 Application of foamed concrete, reproduced from (Mohd Sari and Mohammed Sani 2017; Jhatial et al. 2020b)

Density (kg/m^3)	Application
300 to 600	Used as a replacement for the existing soil, soil stabilization, raft foundation
500 to 600	Utilized in road construction as well as to stabilize a redundant, geotechnical rehabilitation and soil settlement
600 to 800	Used as an alternative to void filling
800 to 900	This density of foamed concrete is used to produce lightweight blocks and other non-load bearing building element. These non-load bearing elements include balcony railing, partition walls, parapets, etc.
1100 to 1400	This density foamed concrete is utilized in prefabrication and cast in place wall. It is can also be used for both load bearing and non-load bearing elements
1100 to 1500	Housing applications
1600 to 1800	Slabs and load bearing elements such as external walls, where significantly high strength is required, are developed used this density of foamed concrete

Besides this, concrete, whether lightweight or heavy weight, has to some extent carbon footprint, due to the main component cement. The recent urbanization has caused the demand for cement to increase exponentially. However, during its processing, the cement industry releases carbon dioxide (CO_2) emissions and thus contributes to 7% of total global CO_2 emissions (Benhelal et al. 2013). Researchers and engineers have concentrated on using supplementary cementitious materials (SCMs), particularly waste by-products, as binders, at least partially replacing cement content. Reusing agro-industrial and municipal wastes as a binder in the production of concrete is an eco-friendly way to minimize cement demand and develop eco-friendly concrete. Not only has the demand for cement grown with the urbanization, but also waste material generation has also risen dramatically, and dumping of such waste materials has become a serious solid waste management issue for countries. Malaysia, one of the biggest palm oil producers and annual exporters, generates around 4 million tons of palm oil fuel ash (POFA) (Muthusamy et al. 2015; Sooraj 2013), a waste product of palm oil production. Usually, this toxic waste is sent to landfills without economic benefits. Another large-scale municipal waste produced is eggshells. According to Malaysia Veterinary Department, 11.76 billion eggs were consumed in Malaysia in 2019 and the consumption is expected to rise over the years (Department Veterinary Service Report 2020). Eggs are an inexpensive nutritious source and eggshells are the egg waste commodity that inevitably ends up in landfills without adequate care, instigating major environmental pollution (Jhatial et al. 2019). Though Malaysia is one of the most progressing country among the developing nations, however, its solid waste management is in poor state (Agamuthu and Fauziah 2011). According to the survey report published by Jabatan Pengurusan Sisa Pepejal Negara (2012), Malaysia generates approximately 33,000 tonnes of solid waste per day, out of which 7% is generated by the industries, while the households contribute to 65%. Among the household waste generation, 45% is associated with the food and organic waste. It is estimated that approximately 95% of the municipal solid waste generated by households (Agamuthu and Fauziah 2011) is dumped to landfills with little to no significant treatment. Though sustainable landfills and recycling of waste should be done in order to limit the adverse impacts to human health and environmental pollution, however, due to the economic development being prioritized in Malaysia and less emphasis on sustainable waste management, it has caused serious solid waste management and environmental issues (Agamuthu and Fauziah 2011).

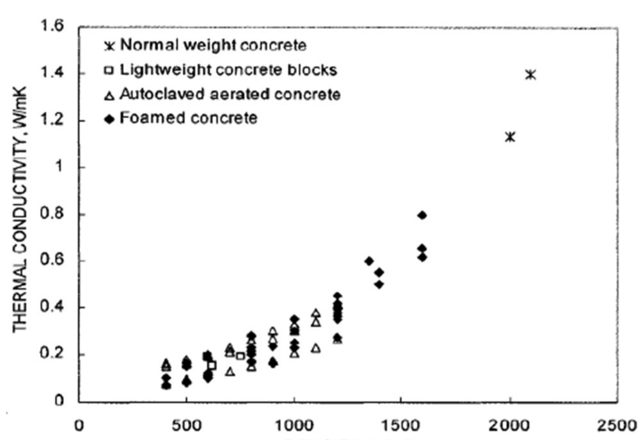


Fig. 2 Influence of density and type of concrete on the thermal conductivity value (Jones et al. 2016)

With the gradual rise in temperatures worldwide due to climate change, higher thermal conductivity and carbon footprint of heavy weight concrete, using LFC as a thermal insulating component in the building is not only a revolutionary idea but also important. It could be the most viable alternative to heavy weight concrete, where a considerable thermal and acoustic insulation as well as lower self-weight is required. By reducing concrete mass, it becomes economic building and can overcome issues of self-weight and high heat transfer. LFC is a perfect solution for heavy weight concrete limitations. Using agro-industrial and municipal wastes such as POFA and eggshell powder (ESP) as partial cement substitute, an eco-friendly LFC can be produced to help minimize cement reliance. Previously, POFA was used as an additive in 1000 kg/m^3 density LFC and shown that it decreases thermal conductivity marginally relative to the controlled specimen (Ganesan et al. 2015). Incorporating POFA and ESP into eco-friendly LFC would not only partially replace the cement material but also provide thermal insulation properties that are urban cities' need of the hour due to UHI influence.

According to ACI 213R-14 (2014), the concrete can be categorized as structural lightweight concrete if it obtains a density ranging from 1440 to 1840 kg/m^3 with compressive strength higher than 17 MPa. Though typical LFC of 1800 kg/m^3 has achieved 17.1 MPa which keeps it barely above the minimum requirement of structural lightweight concrete, however, the addition of SCMs such as POFA, ESP, rice husk ash, fly ash, microsilica and SiO_2 powder in LFC can significantly increase its compressive strength which can range from 20 to 25 MPa; this increase in compressive strength allows to satisfy the structural lightweight concrete's strength criteria, thus allowing it to be used for structural applications (Harith 2018; Karthikeyan et al. 2015).

Research significance

Considering that production of cement contributes to 10% of the global CO_2 pollution (Benhelal et al. 2013; Zhang et al. 2014; Suhendro 2014), and Portland cement contributes to 74 to 81% of the embodied carbon of concrete (Flower and Sanjayan 2007), this study intends to partly substitute cement content with agro-industrial and municipal waste materials, which also creates environmental concerns related to land degradation and shortage. Partial cement supplement can help decrease cement demand and eventually minimize CO_2 emissions. Simultaneously, it can contribute in the reducing the harmful effects of ESP and POFA on the environment and provide a beneficial means instead of landfill disposal (Jhatial et al. 2020a).

Furthermore, in this day and age of global warming, the society faces critical challenges and the demand for energy-saving materials in the construction industry is increasing. To reduce the use of energy and to enhance the comfortability of indoor environments, proper building materials are to be selected, which can perform as thermal insulation (Ganesan et al. 2015) and heat transfer through the material. The UHI effect causes a significant increase in the temperature in urban areas. Excellent thermal insulating properties make LFC a potential substitute to heavy weight concrete to counteract the rise in temperatures in the cities due to UHI. The current research is based upon the following objectives:

1. To determine the physical and chemical properties of the SCMs, POFA and ESP, used in eco-friendly LFC
2. To investigate the fresh state properties and mechanical of eco-friendly LFC
3. To identify the thermal performance in terms of surface temperature and thermal conductivity of eco-friendly LFC
4. To analyse the sustainability in terms of embodied carbon (total CO_2 emissions) for each mix and the eco-efficiency values
5. To obtain the optimum mix of structural eco-friendly LFC incorporating POFA and ESP, which could satisfy the structural lightweight concrete requires as per ACI 213R-14 (2014)

This research focuses, as shown in Fig. 3, on the development of eco-friendly LFC, having cement partially replaced by waste products, reduce the heat transfer and as such counteract the UHI which is increasing the difference in temperature between the urban and its adjacent rural areas. It will be able to provide useful information and exposure in the thermal properties of eco-friendly LFC since the data and statistics in this field is still limited. In addition, this study can help in providing idea and vision to other researchers or engineers in the potential application of eco-friendly LFC.

Research methodology

Materials

LFC is manufactured using binder material (mainly OPC), sand, water and foam (used to reduce the density). In this study, local Tasek CEM I OPC was used, which compiles the cement requirements lied out in ASTM C 150/ C150M-20 (2020). The sand was sieved through 4.75 mm, oven-dried and stored in plastic bags to avoid gaining moisture or unnecessary particles. POFA and ESP were used to replace OPC content in the LFC partially. Furthermore, the Sika foam agent AER 50/50 was used to control the density of the LFC.

POFA was collected from local palm oil mill. POFA is a solid waste ash generated in palm oil mills by burning palm husks and kernel shells and used to generate electricity for the mill itself. According to Tangchirapat et al. (2003), the fineness of the binder material which is to be used in the production of concrete plays a significant role on the strength of concrete; since both POFA and ESP are being substituted as a binder, therefore, they also require adequate fineness. Therefore, the POFA was grounded using the Los Angeles abrasion machine, such that and after grinding, the POFA passed through a 150-μm sieve. Figure 4a demonstrates POFA preparation

Fig. 3 Graphical representation of the research significance

process. The local restaurants, food stalls and bakeries in the vicinity provided the eggshells; however, majority of the eggshells were collected from the Federal Agricultural Marketing Authority (FAMA). These eggshells contained

Fig. 4 Preparation process of **a** POFA and **b** ESP

excessive waste fluid, which may be the egg's membrane, albumen or yolk. Therefore, to eliminate this unwanted fluid, the eggshells were promptly vigorously cleaned with drinking water and then left to dry outdoors. And then the eggshells were oven-dried at a steady temperature of 105°C for 24 hours (Yu et al. 2017). After oven-drying the moisture from the eggshells, the eggshells became crispy, allowing them to be crushed into tiny particles. The shattered eggshells were then placed in Los Angeles abrasion machine and grounded into fine eggshell powder which passed through a 75-µm sieve. The eggshells that retained on 75-µm sieve were grounded again with a handheld blender. Fig. 4b shows the ESP preparing process, and Fig. 5 shows the optical images of POFA and ESP after grinding.

Table 2 shows the physical properties of ESP, POFA and OPC. It is observed that ESP contains a significantly higher specific surface area which can be attributed to the open porosity of the ground powder. The particle morphologies of OPC, ESP and POFA are shown in Fig. 6. It was observed that OPC had irregular-shaped non-spherical particles, which contributes to stronger particle interlocking and thus increases the surface friction and viscosity of cement paste. While the particle morphology of ESP shows that the particles are irregular, varying from round to popcorn shaped like particles.

Furthermore, the distance between the particles of ESP is slightly more significant than the particles of OPC and is of larger in size. From the particle morphology, it can be seen that POFA has angular as well as irregularly shaped particles with some porous particles. It can also be observed from the particle morphology of POFA that the particle size is much larger than those of OPC and ESP. This is due to the percentage retaining on the 45 µm is approximately 15.77% according to the particle size distribution as shown in Fig. 7, compared to OPC and ESP which had 3.53 and 4.05% particles retaining on 45 µm, respectively. The higher number of particles retaining on 45 µm means that those particles are coarser and more porous.

X-ray fluorescence (XRF) test was conducted to study and determine the elemental chemical composition of the material. The chemical composition of POFA and ESP, as well as OPC, is shown in Table 3, which indicates that POFA contains significant SiO_2. The pozzolan materials which are to be used in concrete as SCMs or as additive material are categorized by ASTM C618-19 2019. The sum of SiO_2 + Al_2O_3 + Fe_2O_3 of POFA, which is used in this study, totals 61.75% and can be categorized as Class C pozzolanic material according to ASTM C618-19 2019.

Fig. 5 Optical images of **a** ESP and **b** POFA

The ESP showed a significantly high concentration of CaO; as a matter of fact, it recorded more CaO than the OPC, which can be beneficial, as the POFA can consume the extra CaO and undergo the pozzolanic reaction; thus, it can give extra strength. During the pozzolanic reaction, the $Ca(OH)_2$ is consumed, and additional C-S-H gel is formed. This C-S-H gel is known to be responsible for achieving strength. Normally, POFA has been used as a cement replacement and consumes the freely available $Ca(OH)_2$ in cement during the pozzolanic reaction, but the cement can only provide limited freely available $Ca(OH)_2$. With the addition of calcium-rich ESP, the additional freely available $Ca(OH)_2$ can be consumed during the pozzolanic reaction to enhance further and develop the C-S-H gel, ultimately improving the strength.

Mix design and specimen preparation

Table 4 enlists a total of eight mix proportions of eco-friendly LFC incorporating different POFA and ESP contents. The sand-binder ratio was kept constant at 2:1. According to the British Cement Association (1994), the w/c ratio should be between 0.5 and 0.6. Since both POFA and ESP have been grounded into fine particles to be used as partial binders and have been reported to absorb water, therefore, the 0.55 water-binder (w/b) ratio was used. Meanwhile, the ratio between the foaming agent and water in the foam generator can be customed according to the needs; in this study, the ratio was taken as 1:20 following previous studies. Based upon the previous literature, the POFA contained was taken 20 to 25% while 5 to 15% ESP by weight of cement to substitute cement content.

Table 2 Physical properties of OPC, POFA and ESP, reproduced from Jhatial et al. (2020a)

Physical property	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

An eco-friendly LFC of 1900 kg/m^3 target wet density were prepared using different POFA and ESP contents. The LFC specimen with no cement replacement was prepared for reference. Cement was replaced by 20 and 25% POFA and 5 to 15% ESP by weight of total binder, as seen in Table 4. The preparation of LFC is a three-phase procedure:

1. *Slurry preparation*—Initially, the dry raw materials, including sand, are placed in the concrete mixer and allowed to mix for approximately 3 minutes such that the dry materials are uniformly mixed. Then the dry materials are converted into slurry when specified water per the w/b ratio is added gradually and allowed to mix for another 5 minutes.
2. *Foam preparation*—The mix-foam method is employed in this experimental study, where a foaming agent and water are inserted in the foam generator to produce foam.
3. *Mixing of slurry and foam*—Before the addition of foam in the slurry, the density of the wet slurry was measured. The pre-generated foam is quickly added into the mix, each time the foam was added, it was allowed to mix properly with the slurry and then density was determined. This cycle continued until the wet target density was achieved.

Once the mix achieved the wet target density, the prepared mixed slurry was poured into the moulds and was kept on the vibrating table to ensure pure compaction is achieved. The specimens of size 100 × 100 × 100 mm (for compressive strength), 200 × 100 mm (for splitting tensile strength) and 300 × 300 × 50 mm (for evaluating thermal behaviour) were

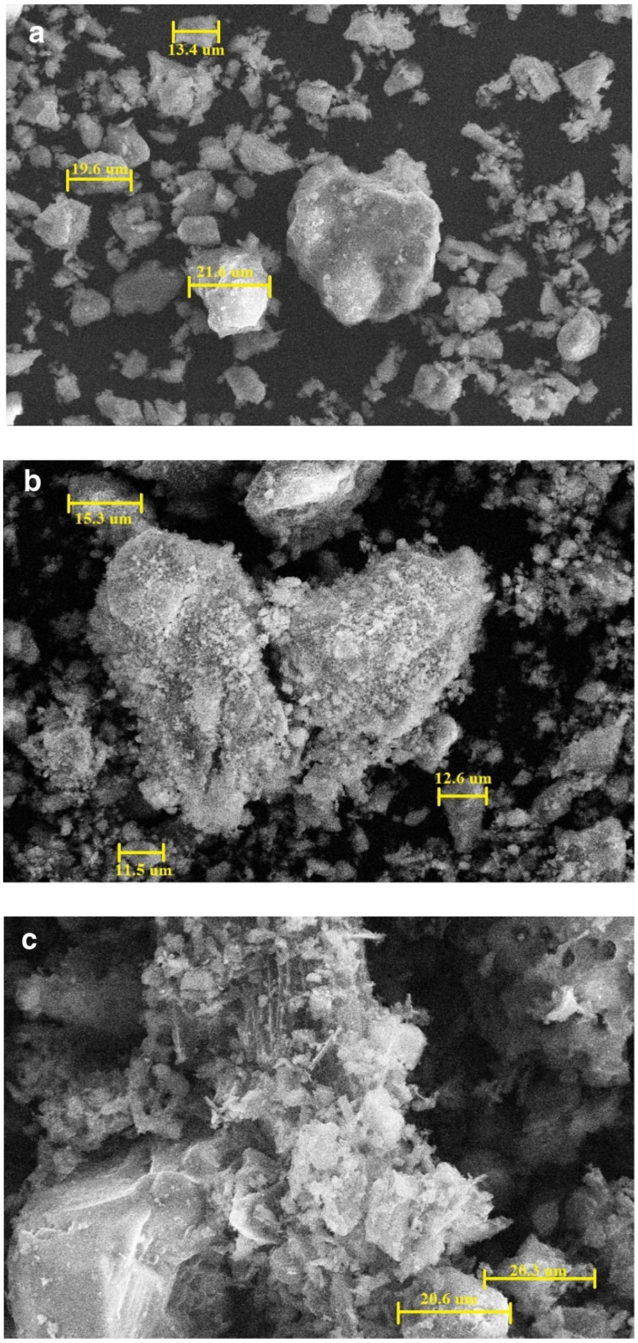


Fig. 6 Particle morphologies of **a** OPC, **b** ESP and **c** POFA

prepared for each mix and kept for 24 hours in open air and then demoulded.

Testing methods

To determine the thermo-mechanical properties of eco-friendly LFC, a comprehensive testing program was designed and followed. Initially, the physio-chemical analysis was done on the binder materials (OPC, POFA and ESP). Once the target wet density was achieved, the workability was determined and then poured into moulds for 24 hours and then removed and put for open-air curing for specified curing age. After achieving the specified curing age, the samples were tested for mechanical properties as shown in Fig. 8 and thermal properties as shown in Fig. 9 and Fig. 10. The summary of the testing program is shown in Table 5.

To evaluate the thermal performance of eco-friendly LFC incorporating waste materials as a cement replacement, two non-destructive tests (surface temperature and thermal conductivity) were conducted. The surface temperature testing setup is illustrated in Fig. 9. A digital infrared thermometer was employed to measure the surface temperature on the concrete samples (Jhatial et al. 2020b; Bevilacqua et al. 2017), whose operational range was −32°C to 600°C, accuracy of 1% and a distance-to-spot ratio of 30:1, and held at 30.48 cm high from the samples. To determine the intensity and influence of the solar radiation on the surface temperature, BABUC pyranometer connected to datalogger was utilized. The surface temperature testing was conducted for 3 days from 10:00 A.M. to 4:00 P.M. (Jhatial et al. 2020b) and the procedure is a modification from Anting et al. (2017) as follows.

a) Panel samples were insulated by polystyrene sheets on all sides except the top surface, which remained exposed to 1-dimensional solar radiation.
b) Solar radiation using the pyranometer and surface temperature using the handheld infrared thermometer were recorded at 15 minutes intervals.
c) Mean sample surface temperature was determined from data.

During the testing, the surface temperature was noted at five different surface points of each specimen; however, this paper discusses the mean readings. Furthermore, the surface temperature measurement was a non-destructive test; therefore, the same samples were used to determine the thermal conductivity. Four holes of various depths were drilled into the concrete, as shown in Fig. 10, such that thermocouples may be inserted which could record the change in temperature during the testing (Jhatial et al. 2020b). The sample panels were placed between the cold plate and the hot plate at 18 and 40°C, respectively, according to BS EN 12664:2001 (2004). The thermal conductivity for each panel was 24 hours, and temperature measurements were taken every 30 minutes.

Results and discussion

Fresh properties

The workability of eco-friendly LFC was determined using J-ring test by comparing the test result from two different portions of the sample. Based on the results tabulated in Table 6,

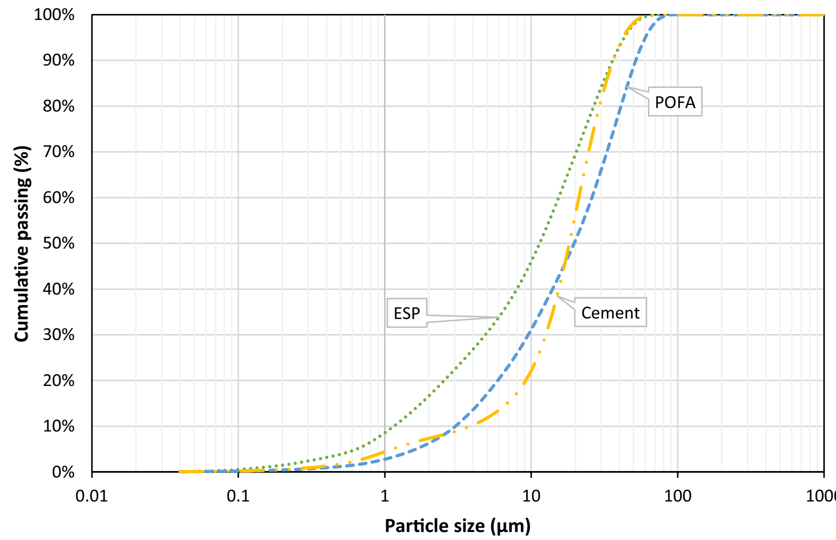


Fig. 7 Particle size distribution curves of binders, reproduced from Jhatial et al. (2020a)

the M0 sample of LFC showed the maximum flowability. But with the increase in SCM content, the flowability decreased significantly. The increase in POFA and ESP contents in the mixture resulted in the restriction to flow of concrete. This restriction is attributed to the high surface area of POFA and ESP particles that require more water achieving ease in movement and rolling of particles over each other. The specific gravity of POFA was 2.12; the lower the value of specific gravity, the higher the water required to achieve similar workability as concrete with no POFA. Though the workability was reduced with increase in POFA and ESP contents, the difference between slump flow and J-ring flow remained between 0 and 25 mm for all mix proportions, and no visible blockage was observed in any of the mixtures.

Table 7 shows the wet density (fresh state) at the time of pouring the mix in the moulds and the dry density (hardened state) at 7 and 28 days. Since the dry target density for this experiment was 1800 kg/m^3, therefore, 1800 ± 100 kg/m^3 wet density was acceptable.

As seen in Table 7, the wet density ranged between 1840 and 1908 kg/m^3, well within the tolerance range. The wet density was kept higher than the target dry density of 1800 kg/m^3 because the addition of foam in the concrete will gradually reduce the density after curing. The dry density of 28 days air-curing samples was recorded, which ranged from 1773 kg/m^3 achieved by the M0 to 1877 kg/m^3 achieved by M2. The dry density recorded agreed to an acceptable tolerance. The dry density for M0 sample reduced lower than the target density due to the uniformly distributed air bubbles (voids), while other mixes contained POFA and ESP; these fine materials had lower specific gravity as well as higher specific surface area. Thus, they provided a coating/cover to the smaller air bubbles, thus significantly preventing them from merging into bigger bubbles. The development of additional C-S-H gels due to the pozzolanic activity also influenced or blocked the air voids. The decrease in the development of air voids meant that the reduction in density was restricted and as such, the compressive strength of LFC will be increased. According to Brady et al. (2001), the acceptance criteria for wet density should be ± 50 kg/m^3 of the specified target density, but for denser mixes having a wet density more than 1800 kg/m^3 ± 100 kg/m^3 are also acceptable. Furthermore, the variability of dry density of 28-day hardened LFC should not exceed ± 100 kg/m^3 of the mean density.

Mechanical properties

Compressive strength

The average compressive strength of LFC is shown in Fig. 11 and Table 8. The compressive strength of M0 was 14.25 and

Table 3 Chemical composition of OPC, POFA and ESP, reproduced from Jhatial et al. (2020a)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	C	SO_3	P_2O_5	LOI
OPC	63.95%	20.61%	3.95%	3.46%	1.93%	-	-	3.62%	-	2.18
POFA	8.10%	51.83%	2.32%	7.60%	3.13%	13.72%	0.28%	2.23%	4.30%	6.29
ESP	88.76%	1.63%	-	0.05%	0.91%	0.24%	-	0.81%	-	7.6

Table 4 Mix proportions and amount of quantities to produce $1m^3$ 1800 kg/m^3 density 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
M0	100	0	0	535.21	0	0	1070.42	294.37	0.30	6.06	125.06
M1	80	20	0	428.17	107.04	0	1070.42	294.37	0.30	6.06	125.06
M2	75	20	5	401.41	107.04	26.76	1070.42	294.37	0.30	6.06	125.06
M3	70	20	10	374.65	107.04	53.52	1070.42	294.37	0.30	6.06	125.06
M4	65	20	15	347.89	107.04	80.28	1070.42	294.37	0.30	6.06	125.06
M5	70	25	5	374.65	133.80	26.76	1070.42	294.37	0.30	6.06	125.06
M6	65	25	10	347.89	133.80	53.52	1070.42	294.37	0.30	6.06	125.06
M7	60	25	15	321.13	133.80	80.28	1070.42	294.37	0.30	6.06	125.06

17.1 MPa at 7 and 28 days, respectively. It can be seen that the addition of ESP along with POFA as SCMs was beneficial in achieving higher compressive strength compared to M0 sample. As ESP is rich in CaO content and by hydration produces the $Ca(OH)_2$ which is consumed during the pozzolanic process triggered by POFA in the presence of water. The highest compressive strength by combined POFA and ESP was recorded by sample M5, with 32.16% higher strength than M0 sample. The presence of highly reactive silica in POFA itself is the main reason behind the increase in compressive strength. The silica content of POFA allows the pozzolanic process to occur, in which $Ca(OH)_2$ is consumed to produce additional C-S-H gel.

The creation of additional C-S-H gel causes LFC to become denser, and this additional C-S-H is responsible for the gain in strength. According to previous studies, the cement can be replaced with reactive silica POFA up to 20% successfully, but further increase in POFA content beyond 20% starts to lose its strength. This can be attributed to the low calcium-silica ratio of POFA and limited free calcium available in cement limits the pozzolanic reaction and thus limits the strength gain in concrete. With the additional $Ca(OH)_2$ provided by ESP, the POFA content can also be increased. Based upon the results obtained, the addition of CaO-rich ESP in LFC along with POFA which is SiO_2-rich was proven to be successful in enhancing the compressive strength of LFC.

Table 5 Summary of experimental testing program

Property		Materials	Mixes	Samples	Curing age	Standard
Material testing	Chemical composition (XRF)	OPC, POFA and ESP	-	-	-	(ASTM C114 - 18 2018)
	Particle size distribution	OPC, POFA and ESP	-	-	-	-
Fresh state property	Workability	-	M0, M1, M2, M3, M4, M5, M6, M7	-	Wet state	ASTM C1621/C1621M (2008)
Mechanical properties	Compressive strength	-	M0, M1, M2, M3, M4, M5, M6, M7	3 cubes for each curing age per mix.	7 and 28 days	(BS EN 12390-3 2019)
	Splitting tensile strength	-	M0, M1, M2, M3, M4, M5, M6, M7	3 cylinders for each mix.	28 days	(BS EN 12390-6 2009)
	Modulus of elasticity	-	M0, M1, M2, M3, M4, M5, M6, M7	3 cylinders for each mix.	28 days	ASTM C469 (2014)
Thermal properties	Surface temperature	-	M0, M1, M2, M3, M4, M5, M6, M7	3 panels for each mix.	28 days	Non-destructive test modified from Anting et al. (2017)
	Thermal conductivity	-	M0, M1, M2, M3, M4, M5, M6, M7	3 panels for each mix.	28 days	BS EN 12664:2001 (2004)

Fig. 8 LFC samples under compressive and splitting tensile strength testing

However, the increased cement replacement showed a gradual decrease in compressive strength. This reduction in compressive strength can be attributed to (1) the excessive $Ca(OH)_2$, with the addition of a higher percentage of ESP, which is not entirely consumed during the pozzolanic reaction, and with a higher percentage of POFA content means reduced cement content and (2) the result of a clinker dilution effect which is a consequence of partially replacing cement using SCMs, in this case, POFA and ESP.

It was observed that the LFC containing combined SCMs of more than 40% produces lower strength than M0 LFC; this may be due to the lesser amount of total C-S-H gel produced. Significantly reduced cement content also causes reduced hydration process in the concrete and leads to developing lower amount of hydration products not only C-S-H. This adverse effect when excessive POFA is utilized as cement replacement has also been reported by other researchers (Muthusamy et al. 2015).

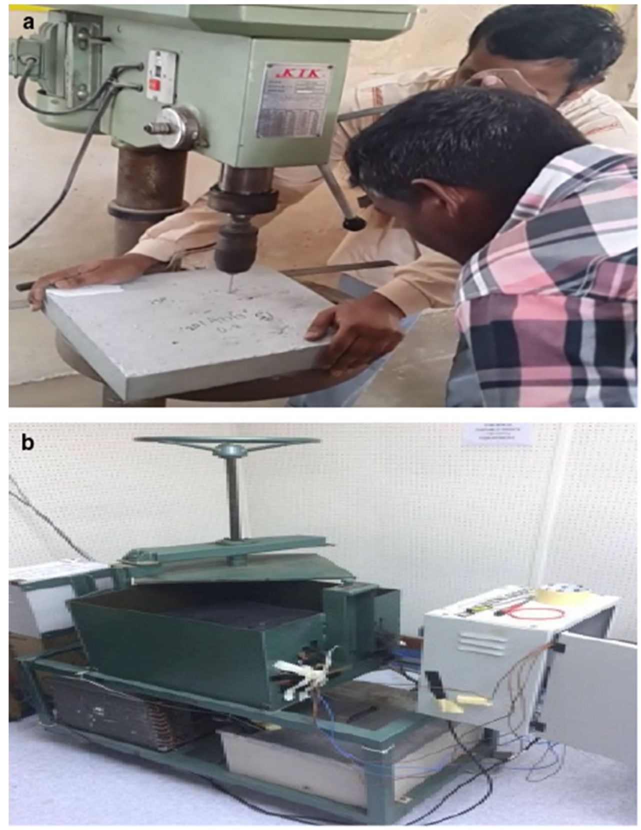


Fig. 10 **a** Drilling holes in the samples, **b** thermal conductivity apparatus

Splitting tensile strength

From Fig. 12 and Table 9, it can be observed that the tensile strength of M0 sample with no POFA and ESP is 2.07 MPa when tested after 28 days air-curing. With the replacement of cement with 20% POFA (M1 sample), the splitting tensile strength dropped to 1.97 MPa, which was 4.83% reduction. The average tensile strength of LFC containing 20% POFA and 5% ESP (M2) was 2.61 MPa, which was 26.09% higher than the M0 sample and 32.49% higher than the 20% POFA

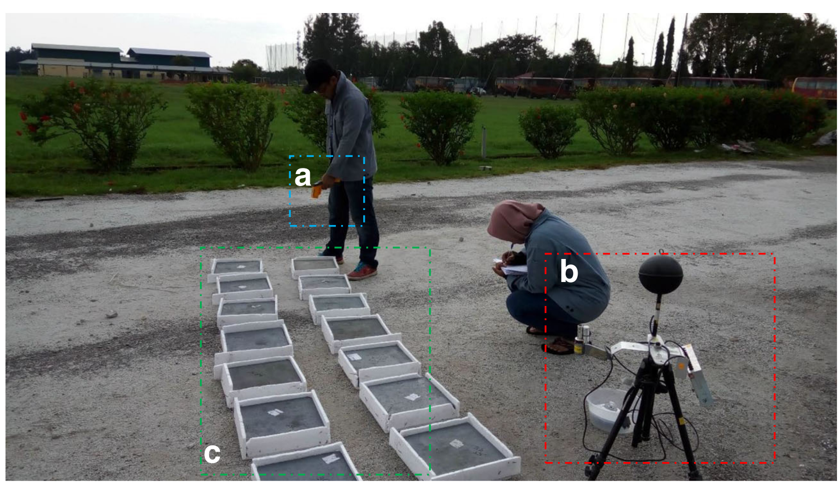


Fig. 9 Surface temperature testing: **a** infrared thermometer, **b** BABUC pyranometer with datalogger, **c** 1-dimensional exposure of samples

Table 6 The result from the J-ring test of each mix proportion

Mix	Slump flow (mm)			J-ring flow (mm)			Difference between a slump and J-ring flow	Type of blocking
	d1	d2	$\frac{d1+d2}{2}$	d1	d2	$\frac{d1+d2}{2}$		
M0	533	528	531	520	520	520	11	No blocking
M1	430	428	429	425	400	413	16	No blocking
M2	398	390	394	385	370	378	16	No blocking
M3	383	377	380	370	360	365	15	No blocking
M4	420	410	415	419	376	398	17	No blocking
M5	419	415	417	415	390	403	14	No blocking
M6	399	397	398	385	380	383	15	No blocking
M7	455	453	454	440	430	435	19	No blocking

LFC (M1). With further increase in ESP content (M3), the tensile strength decreased slightly to 2.55 MPa, which although was lower than M2 samples, it was still 23.19% higher than the M0 sample and 29.44% higher than 20% POFA LFC (M1). The addition of 15% ESP in 20% POFA LFC (M4) recorded an average of 1.81-MPa tensile strength, which was a significant decrease, approximately 12.56%, compared to M0 sample.

The strength gain by specimens M2~M4 can be attributed to the formation of additional C-S-H gel which was created after the consumption of $Ca(OH)_2$ during the pozzolanic process. But with further increase in POFA content and ESP content alike, showed gradual reduction and loss in strength might be due to reduced cement content lead to weakened bonding between particles, thus allowing the samples to split under tensile load. Like the compressive strength of LFC, the tensile strength also decreases when density is reduced. The behaviour of the tensile strength of LFC is similar to its compressive strength. It is worth noting that the further increase in cement replacement using POFA and ESP decreased the tensile strength rapidly. This decrease is attributed to the dilution effect that is the consequence of higher cement replacement. Another reason to the reduction in tensile strength can be attributed to weakened bonding between particles with further increase in POFA and ESP content; thus, gradual reduction and loss in strength occur allowing the samples to split under tensile load.

Modulus of elasticity and Poisson's ratio

The results obtained from the modulus of elasticity (MoE) and Poisson's ratio testing of samples are tabulated in Table 10. It can be observed that the MoE of LFC reduces significantly when an increased percentage of cement is replaced by POFA and ESP. The MoE of M0 sample was recorded to be 14394 N/mm^2 while the 20% POFA sample (M1) recorded 15666 N/mm^2. With the addition of 5% ESP content along with 20% POFA (M2), the MoE increased significantly to 27,513 N/mm^2. But with further increase in ESP, the MoE kept on reducing. The Poisson's ratio increased with the addition of ESP along with POFA, which can be attributed to the enhancement in pozzolanic reaction with the addition of ESP also increased the MoE. However, similar to compressive and tensile strengths, the MoE also drops beyond 30 to 35% SCM content. This drop can be attributed to lower content of

Table 7 Change in the density of eco-friendly LFC

Mix	Wet density (kg/m^3)	Dry density on 7 days (kg/m^3)	Reduction in density on 7 days (%)	Dry density on 28 days (kg/m^3)	Reduction in density on 28 days (%)
M0	1840	1837	−0.16	1773	−3.64
M1	1880	1833	−2.50	1833	−2.50
M2	1900	1880	−1.05	1877	−1.21
M3	1899	1850	−2.58	1847	−2.74
M4	1900	1853	−2.47	1853	−2.47
M5	1908	1850	−3.04	1840	−3.56
M6	1877	1853	−1.28	1827	−2.66
M7	1894	1863	−1.64	1833	−3.22

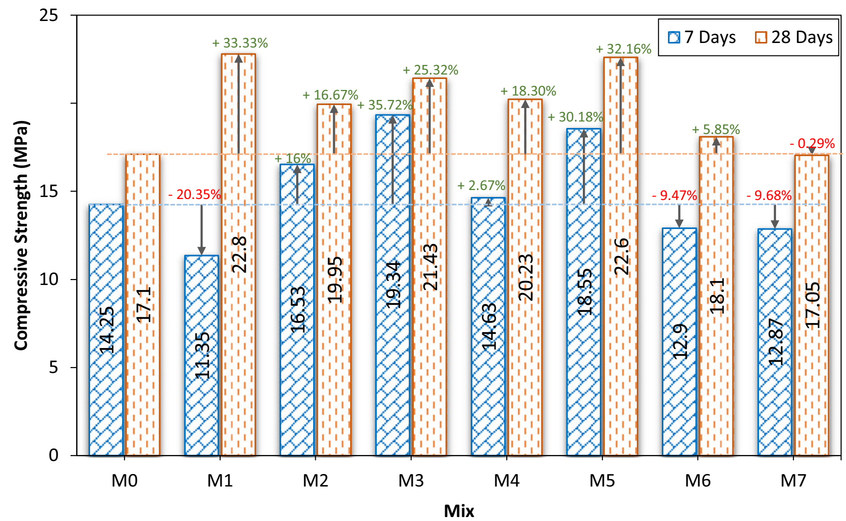


Fig. 11 Average compressive strength of eco-friendly LFC

cement which leads to lower rate of reaction and formation of reduced hydration products.

Thermal properties

Surface temperature

Fig. 13 depicts the surface temperature from 10 A.M. to 4 P.M. on three consecutive days. Table 11 summarizes surface temperature results. Based on the results, surface temperature at maximum sun intensity is not the maximum surface temperature that could be reached. Maximum solar radiation was observed at 12:00 P.M. which was 1495 W/m^2. The lowest surface temperature was reported for M0, which was 51.42°C in case of maximum solar radiation, while the surface temperature for other POFA and ESP samples was marginally higher. The peak surface temperature occurred after 60 minutes, with M0 recording 52.52°C, while sample M1 recorded the maximum temperature of 54.60°C, 2.08°C higher than sample M0. The surface temperature decreased slightly with ESP. The discrepancy between the M0 sample's maximum surface temperature and the maximum surface temperature of samples containing POFA and ESP decreased as the ESP content increased.

In day 2, 1446 W/m^2 was the highest solar radiation at 12:30 P.M. The maximum surface temperature was 47.24°C, reported at M5, 1.84°C higher than M0. The highest surface temperature for all samples occurred within 75 minutes of the moment that maximum solar radiation was observed. The peak surface temperature of M1 was 56.78°C, which was around 1.74°C higher than the peak surface temperature of M0 samples 55.04°C. With increased ESP content, the panels reported marginally lower peak surface temperature. With M2, the peak surface temperature was 55.56°C, as the ESP content was increased to 10% (M2), it decreased to 55.12°C and further increased to 15% ESP (M3), the peak surface

Table 8 Results of compressive strength of eco-friendly LFC

Mix	7 days					28 days				
	Average (MPa)	Difference w.r.t M0 (%)	Variance	Error	Standard deviation	Average (MPa)	Difference w.r.t M0 (%)	Variance	Error	Standard deviation
M0	14.25	-	0.123	0.202	0.350	17.10	0.00	0.090	0.173	0.300
M1	11.35	−20.35	0.107	0.189	0.328	22.80	33.33	0.390	0.361	0.624
M2	16.53	16.02	0.093	0.176	0.306	19.95	16.67	1.778	0.770	1.333
M3	19.34	35.72	1.782	0.771	1.335	21.43	25.34	0.003	0.033	0.058
M4	14.63	2.69	0.123	0.203	0.351	20.23	18.32	0.053	0.133	0.231
M5	18.55	30.18	0.843	0.530	0.918	22.60	32.16	0.210	0.265	0.458
M6	12.90	−9.47	0.753	0.501	0.867	18.10	5.85	1.960	0.808	1.400
M7	12.87	−9.71	0.043	0.120	0.208	17.05	−0.29	0.003	0.029	0.050

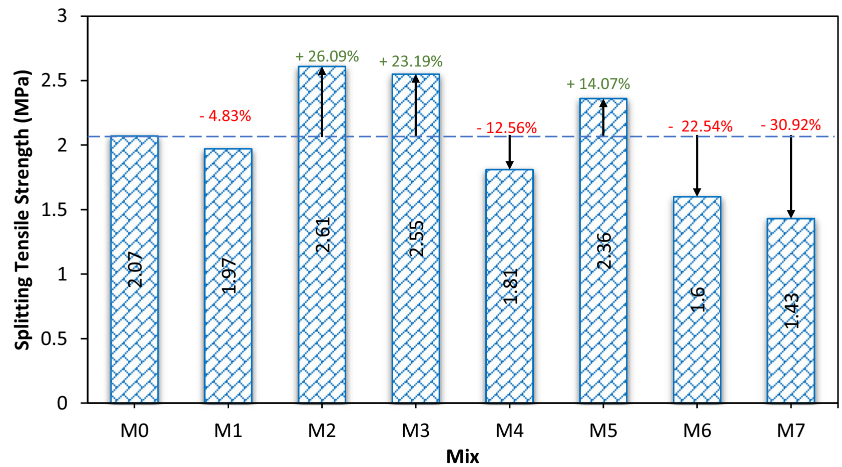


Fig. 12 Average splitting tensile strength of eco-friendly LFC

temperature decreased to 55.06°C. A similar pattern was observed with further rise in POFA content, with the addition of ESP holding peak surface temperature down.

The maximum solar radiation was 1490 W/m^2 for day 3, which was recorded at 12:15 P.M. The surface temperature at the maximum solar radiation was highest for the M0 sample, 47.92°C, while for other samples containing POFA and ESP, it was slightly lower. However, after 30 minutes, the peak surface temperature was recorded for all mix samples. The peak surface temperature was 52.28°C, which was observed on the surface of M7 samples. This peak surface temperature was approximately 1.34°C higher than the M0 sample.

The maximum solar radiation was determined to be between 1446 and 1495 W/m^2 on three consecutive days. The highest solar radiation prevailed between 12:15 P.M. and 1:00 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. Maximum surface temperature was registered 15–75 minutes after maximum solar radiation occurred. The increase in surface temperature above the temperature recorded at maximum solar radiation is attributed to the conversion of radiation to atoms in materials as some object receives solar radiation. Eventually, this absorbed radiation is released by the material as heat, thus heating the surface of the material further. This process will differ in speed and intensity depending on material properties. The M0 sample shows a comparatively lower rise from surface temperature measured at maximum solar radiation to later recorded maximum surface temperature confirmed by previous studies (Jhatial et al. 2020b).

Materials with relatively lower albedo tend to absorb more heat from the solar radiation, resulting in higher surface temperatures, whereas materials with higher albedo behave opposite, absorbing lesser heat from solar radiation, thus resulting in cooler surface temperatures. A blackish coloured surface, that has 0 albedo, absorbs literally all the solar radiation it receives, while whiter coloured surfaces, with 1 albedo, reflect the solar radiation (Ibrahim et al. 2018). Low albedo surfaces' ability to absorb solar radiation heats up the material and is then reradiated, raising the surrounding ambient air temperatures. Concrete having low albedo is one of the main contributors to high air temperatures and thermal discomfort (Ibrahim et al. 2018) (Mohajerani et al. 2017). It was observed that higher content of POFA when incorporated in the fabrication of LFC converted the surface colour of concrete from light grey to darker grey, thus reducing the albedo, subsequently effecting the surface temperature, as observed in Table 11. Though not intentional, the inclusion of POFA may contribute

Table 9 Results of splitting tensile strength of eco-friendly LFC

Mix	Average (MPa)	Difference w.r.t M0 (%)	Variance	Error	Standard deviation
M0	2.07	---	0.126	0.205	0.355
M1	1.97	−4.99	0.311	0.322	0.558
M2	2.61	26.09	0.040	0.115	0.200
M3	2.55	23.19	0.034	0.106	0.184
M4	1.81	−12.40	0.129	0.207	0.359
M5	2.36	14.17	0.006	0.043	0.075
M6	1.60	−22.54	0.038	0.113	0.195
M7	1.43	−30.76	0.141	0.217	0.375

Table 10 Results of modulus of elasticity and Poisson's ratio of eco-friendly LFC

Mix	Modulus of elasticity (MoE)		Poisson's ratio	
	Average (N/mm^2)	Difference (%)	Average	Difference (%)
M0	14394	---	0.25	---
M1	15666	+ 8.84	0.16	−36
M2	27513	+ 91.14	0.29	+ 16
M3	22077	+ 37.38	0.19	−24
M4	19957	+ 38.65	0.34	+ 36
M5	25721	+ 78.69	0.18	−28
M6	15138	+ 5.17	0.49	+ 96
M7	12157	−15.54	0.15	−40

to UHI, however, as to what magnitude is yet to be determined. It is believed that the contribution will be limited, as the inclusion of POFA and ESP reduced the thermal conductivity value, reducing the thermal discomfort in the building and thus reducing the requirement of air-conditioning.

Thermal conductivity

Previously, it has been found that the 2240 kg/m^3 density heavy weight concrete has a thermal conductivity of 1.3 W/mK (Soebarto 2009), and this value can be reduced with the use of LFC. Fig. 14 tabulates the overall results of thermal conductivity. This study shows that the average thermal conductivity of the M0 sample with a dry density of 1800 kg/m^3 LFC was determined to be 0.82 W/mK (Jhatial et al. 2020b), due to the development of pore voids in the LFC matrix (Jhatial et al. 2020b), which is significantly lower than the thermal conductivity of heavy weight concrete.

The LFC with 20% POFA (M1) recorded 0.54 W/mK thermal conductivity value which was approximately 34.15% less than the M0 sample. With the addition of 5% ESP to 20% POFA (M2), the thermal conductivity value marginally increased to 0.63, but with further increase in ESP content, the thermal conductivity value reduced, such that for samples containing 20% POFA and 15% ESP (M4), the thermal conductivity value reduced to 0.58 W/mK which is 29.29%. The thermal conductivity value slightly increased with the increase in the POFA content. The decrease in the thermal conductivity of eco-friendly LFC incorporating POFA and ESP may be attributed to the delayed POFA pozzolanic reaction and the presence of more voids in matrix. A previous study (Mo et al. 2017) found that the thermal conductivity value can be reduced from 15 to 50 % by partially substituting cement content with POFA. From the study, the addition of POFA and ESP as cement substitute in LFC will reduce the thermal conductivity from 23 to 35% compared to the M0 study, which is correlated to previous findings. The difference in thermal conductivity reduction is due to increased POFA and ESP materials.

Though there exist many other potential materials, such as graphene nanoplates (Zheng et al. 2017) (Qiu et al. 2018), expanded poly-lactic acid (Bai et al. 2018; Sayadi et al. 2018), expanded vermiculite (Sayadi et al. 2018), carbon nanotubes and different polymers (Li et al. 2019; Zhang et al. 2019), which have the capability to reduce the thermal conductivity value when utilized in concrete beyond what has been found in this study, however, some of the materials which are ideal for developing thermally insulating building materials are very expensive. Whereas the utilization of POFA and ESP has many advantages such as they are already waste materials which do not have any significant value, and thus disposed of in landfills, which cause severe health issues, thus, reuse of such materials is beneficial. Furthermore, when POFA and ESP are used in the production of concrete, they are utilized as SCMs and partially replace the cement content, though the small reduction is made; if the waste recycling in concrete is taken more seriously and implemented throughout the world, the slight reduction could have a significant impact on the CO_2 gas emissions. Additionally, with the rapid depletion of natural resources, a coarse-free concrete with the benefits of reduced cement content and thermal insulation is the need of the hour.

Sustainability analysis

CO_2 emissions

In this study, the equivalent CO_2 emission values for OPC, water, foaming agent and fine aggregates were taken from literature. For POFA, the CO_2 emissions were calculated according to the method described by Alnahhal et al. (2018) who took into consideration the CO_2 emissions during transportation, drying and grinding processes. However, the distance was modified, since the distance from the palm oil mill to the laboratory where the experimental work was done was approximately 50 km. The electricity consumed for oven-drying POFA for 24 hours at 105°C is at a rate of 1041.67 W/h (Alnahhal et al. 2018). According to DECC (2011), the CO_2 emission factor for each kilowatt-hour of electricity consumed is 0.521 $kgCO_2/kWh$, while 0.192 kg CO_2 is emitted for every kilometre the material is transported.

To the best of the authors' knowledge, there is unavailability of the embodied carbon of ESP in the literature; therefore, the equivalent CO_2 of ESP has been estimated on few assumptions that production of ESP involves transportation, cleaning, drying, grinding and sieving. Based on the technical specifications of eggshell grinding machine (Egg-machine.com 2021), 9, 4 and 0.37kWh electricity is consumed per 60 kg for drying, grinding and sieving of eggshells, respectively. Although the eggshells

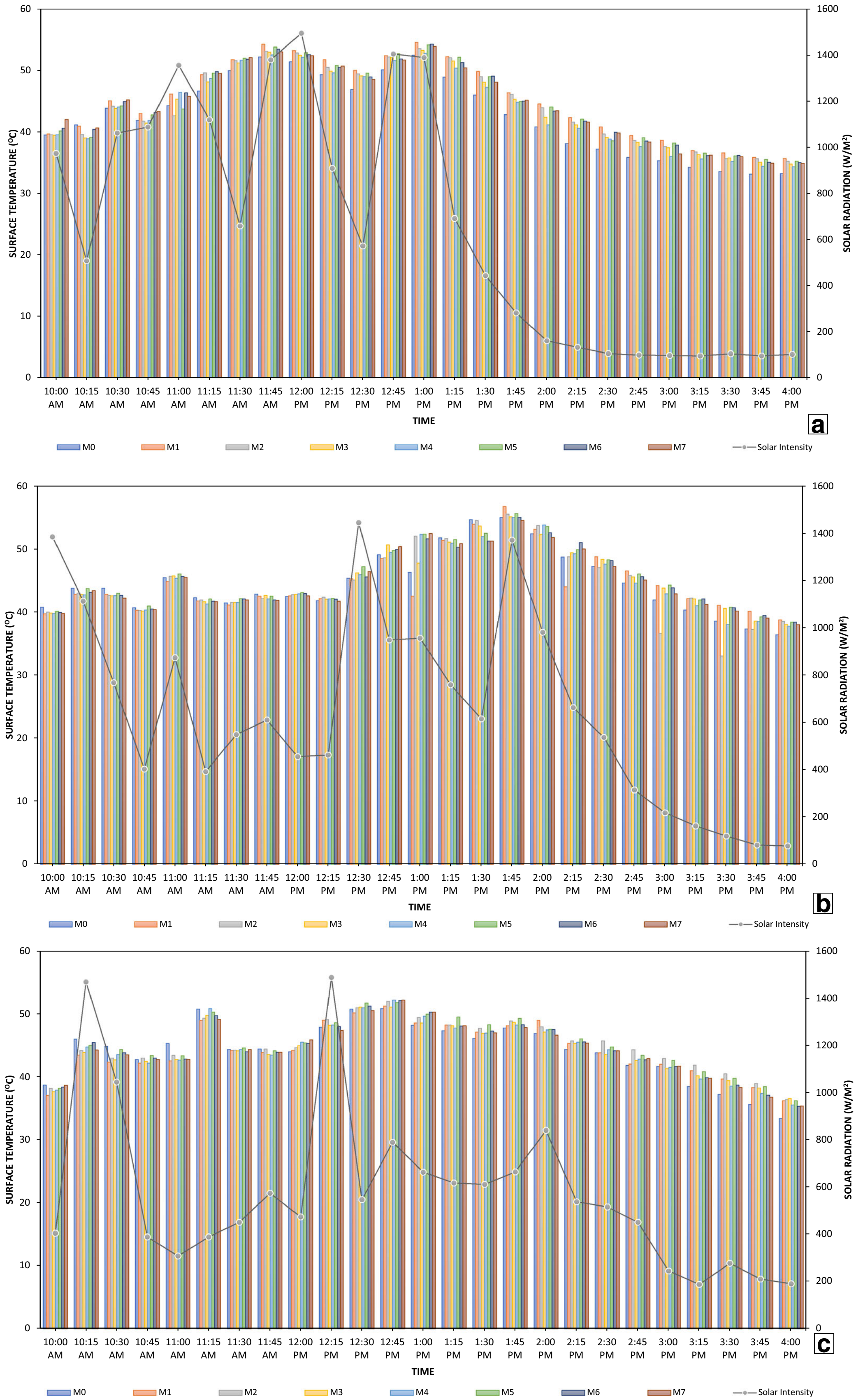


Fig. 13 Surface temperature readings on **a** day 1, **b** day 2 and **c** day 3

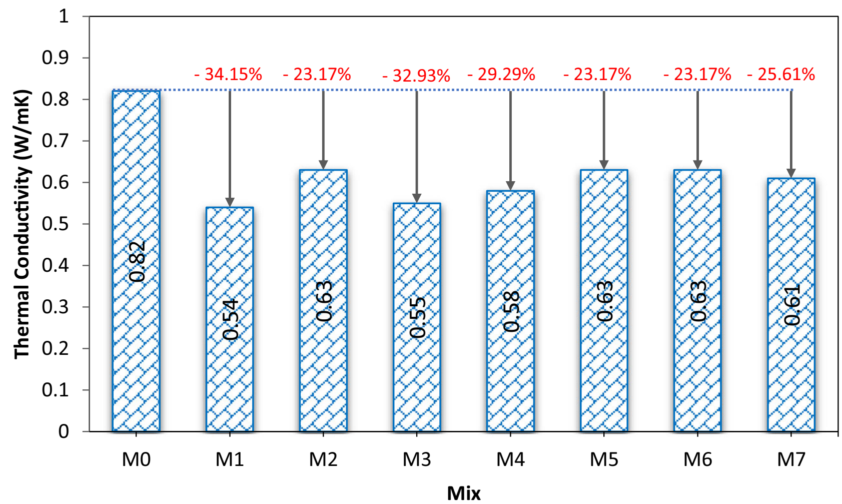
Table 11 Surface temperature

Testing day	Mix	Max. solar radiation			Peak temperature		Difference	
		Intensity (W/m^2)	Surface temp. (°C)	Time	Surface temp. (°C)	Time	Surface temp. (°C)	Time difference (minutes)
Day 1	M0	1495	51.42	12:00 p.m.	52.52	1:00 p.m.	+ 1.10	60
	M1		53.24		54.60		+ 1.36	
	M2		52.86		53.58		+ 0.72	
	M3		52.50		53.30		+ 0.8	
	M4		52.16		52.84		+ 0.68	
	M5		52.90		54.18		+ 1.28	
	M6		52.60		54.26		+ 1.66	
	M7		52.44		53.90		+ 1.46	
Day 2	M0	1446	45.40	12:30 p.m.	55.04	1:45 p.m.	+ 9.64	75
	M1		45.30		56.78		+ 11.48	
	M2		45.12		55.56		+ 10.44	
	M3		46.24		55.12		+ 8.88	
	M4		45.98		55.06		+ 9.08	
	M5		47.24		55.66		+ 8.42	
	M6		45.60		55.06		+ 9.46	
	M7		46.46		54.56		+ 8.1	
Day 3	M0	1490	47.92	12:15 p.m.	50.94	12:45 p.m.	+ 3.02	30
	M1		49.06		51.32		+ 2.26	
	M2		49.24		52.08		+ 2.84	
	M3		48.58		51.16		+ 2.58	
	M4		48.28		51.2		+ 2.92	
	M5		48.68		51.9		+ 3.22	
	M6		48.06		52.22		+ 4.16	
	M7		47.46		52.28		+ 4.82	

were collected from different food stalls and bakeries, however, majority of the eggshells were collected from FAMA, Rengit, Malaysia, which was approximately 31 km away from the laboratory. Considering a diesel lorry was utilized for delivering 1000 kg of ESP, the equivalent CO_2 emissions for transportation are calculated as shown in Table 12. According to the calculations provided in Table 12, the total CO_2 emissions due to electricity and fuel (diesel) consumption for processing and transportation of POFA and ESP were 0.100619 and 0.12205 kgCO_2/kgSCM, respectively. Table 13 shows the equivalent CO_2 emissions for all materials which are used in the current study.

Based on the equivalent CO_2 emissions as shown in Table 13 for each material per kilogram, Table 14 summarizes the total CO_2 emissions which are estimated for the production of 1m^3 concrete. As observed from Table 14, the highest CO_2 emission among all the mixes in this study was for M0 which is 453.97 kgCO_2/m^3. The sole contributor to the CO_2 emissions for control sample M0 is the OPC, which accounts to 96.67%. Though OPC is responsible for 74 to 81% of total CO_2 emissions during the fabrication of concrete (Flower and Sanjayan 2007), however, its staggering contribution in the fabrication of LFC is due to the fact that LFC is prepared without coarse aggregate; therefore, it is basically just OPC and sand. This CO_2 emission has been hypothesized to be reduced with the use of SCMs. The concrete M1, which substitutes 20% OPC content with POFA, exhibited 376.97 kgCO_2/m^3 emissions which is 16.96% lower than the control M0. Further substitution in OPC content in the concrete leads to further reduction in total CO_2 emissions. The maximum reduction of 33.55% was observed in M7, in which 40% OPC content was substituted by POFA and ESP. In this study, the calculated CO_2 emissions for concrete incorporating SCMs prove that the utilization of waste materials in concrete could significantly reduce the CO_2 emissions during the fabrication of concrete. As the substitution level of OPC with SCMs increased, the average CO_2 emissions of the concrete also decreased. In this study, the binder (OPC + SCMs) was the most significant contributor to CO_2 emissions at rates ranging from 95 to 96.67% of the total emissions of 1 m^3 LFC, depending on the replacement ratio and the type of SCMs used.

Fig. 14 Average thermal conductivity of eco-friendly LFC



According to Bheel et al. (2021), the embodied carbon of control concrete was 328.57 kgCO_2/m^3, however, with substituting cement content with 5, 10, 15 and 20% coconut shell ash, resulted in reduction of 3.82, 7.38, 11.20 and 14.77%, respectively. According to Flower and Sanjayan (2007), to produce 25-MPa heavy weight concrete generated approximately 290 kgCO_2/m^3 embodied CO_2. With a substitution of 25% OPC content with fly ash, the embodied carbon reduced to 253 kgCO_2/m^3 which is 12.76% lower than the concrete with 100% OPC content. In a study conducted by Alnahhal et al. (2018), a 30-MPa concrete was designed, in which the embodied carbon for the control sample with natural aggregates was determined to be 369 kgCO_2/m^3, with the complete substitution of natural aggregates with recycled aggregates, and the embodied carbon was found to be 342 kgCO_2/m^3, a merely 7.32% decrease. However, with the substitution of cement content with 10, 20 and 30% POFA in the concrete containing the recycled aggregates, the embodied carbon was determined to be 315, 288 and 261 kgCO_2/m^3, respectively. This was equivalent to 7.90, 15.90 and 23.68% reduction compared to concrete containing 100% OPC and recycled aggregates. Thus, the observed reduction in embodied carbon of concrete with the incorporating SCMs in the current study corresponds with previous findings.

Eco-strength efficiency

Fig. 15 shows the efficiency of all the LFC mixes at different curing ages by comparing compressive strength to CO_2 emissions. It can be seen that the control sample M0 without the inclusion of SCMs has an efficiency of 0.031 and 0.038 MPa/kgCO_2.m^{-3} for 7 and 28 days, respectively. With 20% replacement of OPC with POFA (M1), the eco-efficiency increased by 60.53% to 0.060 MPa/kgCO_2.m^{-3} at 28 days. Islam et al. (2016) found that POFA blended concrete had better eco-efficiency when used at 10–25% replacement levels. Generally, most of the SCMs have the highest eco-efficiency at 20% replacement level (Alnahhal et al. 2018). As since eco-efficiency is linked with the compressive strength, further increase in SCMs results in a reduction in compressive strength, thus resulting in lower eco-efficiency. According to the current study, the combined utilization of POFA and ESP in the fabrication of LFC enhanced the eco-efficiency. All the

Table 12 Calculation of CO_2 emissions of SCMs

Material	Energy requirements for 1000 kg SCM			Transportation of 1000 kg SCM		Emission factor (kg CO_2/kgSCM)	Reference
	Electricity consumption (kWh)		Emission factor (kg CO_2/kWh)	Distance (km)	Emission factor (kg CO_2/km)		
	Drying	Sieving and grinding					
ESP	150	72.84	0.521	31	0.192	0.122052	(Egg-machine.com 2021)
POFA	25	149.7	0.521	50	0.192	0.100619	(Alnahhal et al. 2018)

Table 13 Equivalent CO_2 emission for each material in this study

Materials	$KgCO_2/kg$	Reference
Cement	0.82	(Flower and Sanjayan 2007)
Sand	0.0139	(Turner and Collins 2013)
Water	0.000196	(Yang et al. 2013)
Foaming agent	0.527	(Thevarajah et al. 2020)
Palm oil fuel ash	0.100619	(Alnahhal et al. 2018)
Eggshell powder	0.122052	Current study estimates

mixes with the combined POFA and ESP content (M2, M3, M4, M5, M6 and M7) exhibited significantly higher eco-efficiency values compared to the control M0 mix, ranging from 28.58 to 81.42% and 47.82 to 76.97% for 7 and 28 days, respectively. The highest 28 days eco-efficiency was observed by M5, which contains 25% POFA and 5% ESP, totally 30% cement replacement. However, both M6 and M7 which consist of 25% POFA + 10% ESP (total 35% cement replacement) and 25% POFA + 15% ESP (total 40% cement replacement) exhibited 50% higher eco-efficiency at 28 days compared to control M0 mix, without any loss in compressive strength. Gursel et al. (2016) also observed that lower CO_2 intensities were achieved by replacing cement with SCMs. In addition, García-Segura et al. (2014) concluded that using rice husk ash together with fly ash decreased CO_2 emissions without a significant drop in compressive strength.

Conclusion

In this study, eco-friendly lightweight foamed concrete (LFC) was successfully developed by partially substituting cement content with agro-industrial and municipal waste materials POFA and ESP. It was found that the addition of the agro-industrial and municipal wastes caused a significant reduction in workability due to low specific gravity and high specific surface area of POFA and ESP caused higher water absorption which influenced the workability and density development of specimens.

The mechanical strengths (compressive and tensile) significantly increased when lower POFA and ESP content was utilized. The maximum compressive and tensile strengths achieved were 22.6 and 2.61 MPa, respectively, by M5 mix, which was approximately 32.16 and 26.09% higher than the M0 sample. Though the further increase in the content of POFA decreased the compressive strength, yet it was slightly higher than the M0 samples. However, a further increase in cement replacement resulted in a reduction in compressive and tensile strength. By achieving 22.6 MPa, 28-day compressive strength and in-place density of 1800 kg/m^3, it allows M5 mix to be considered structural lightweight concrete and is suitable for structural purposes.

Furthermore, it was found that the eco-friendly LFC incorporating the different POFA and ESP contents achieved minimum 17 MPa at 28 days and the density within the range of 1440 to 1920 kg/m^3 prescribed in ACI 213R, thus making them suitable for structural applications. In addition to this, the eco-friendly LFC incorporating POFA and ESP achieved significantly lower thermal conductivity, thus indicating that they can be utilized as a thermally insulating building material to energy conservation. However, the increase in POFA and ESP content had an adverse impact on the tensile strength of eco-friendly LFC.

The partial substitution of OPC with combined POFA and ESP was found to be beneficial in eco-strength efficiency (compressive strength with respect to CO_2 emissions) with the highest values obtained for 30% cement replacement level. Overall, the combination utilization of POFA and ESP as a

Table 14 CO_2 emissions for 1 m^3 of concrete

Mix	CO_2 emissions for 1 m^3 of concrete ($kg\ CO_2/m^3$)								
	Binder			Sand	Water	Foam		Total	Difference w.r.t. M0 (%)
	OPC	POFA	ESP			Foaming agent	Water		
M0	438.87	0.00	0.00	14.88	0.06	0.16	0.001	453.97	---
M1	351.10	10.77	0.00	14.88	0.06	0.16	0.001	376.97	-16.96
M2	329.16	10.77	3.27	14.88	0.06	0.16	0.001	358.29	-21.08
M3	307.21	10.77	6.53	14.88	0.06	0.16	0.001	339.61	-25.19
M4	285.27	10.77	9.80	14.88	0.06	0.16	0.001	320.93	-29.30
M5	307.21	13.46	3.27	14.88	0.06	0.16	0.001	339.04	-25.32
M6	285.27	13.46	6.53	14.88	0.06	0.16	0.001	320.36	-29.43
M7	263.33	13.46	9.80	14.88	0.06	0.16	0.001	301.68	-33.55

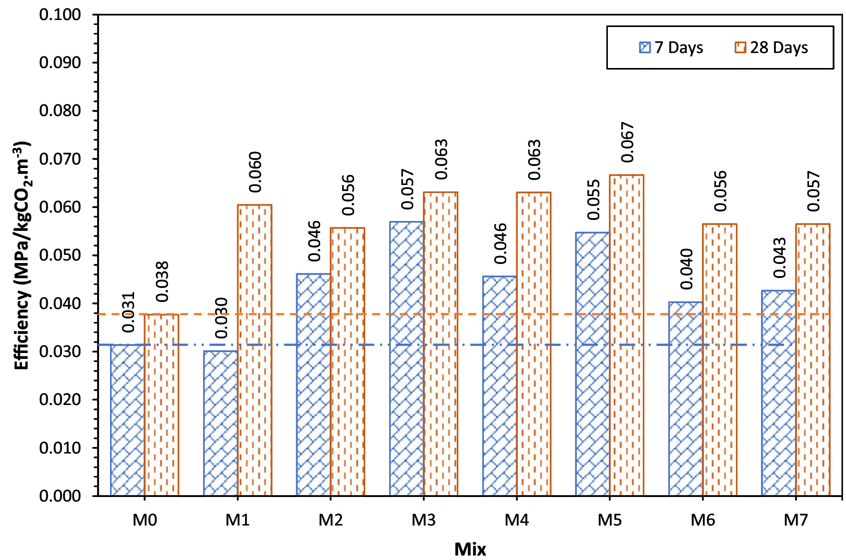


Fig. 15 Eco-strength efficiency of different mixes

supplementary cementitious material not only enhanced the thermo-mechanical performance of eco-friendly LFC but also has reduced the environmental impacts caused by the disposal of POFA and ESP in landfills as well as reducing the total CO_2 emissions during the production of eco-friendly LFC.

Authors' contributions **Ashfaque Ahmed Jhatial**: conceptualization, investigation, data analysis, supervision, writing (original draft), writing (review and editing).

Wan Inn Goh: supervision, methodology, writing (original draft), writing (review and editing), funding acquisition.

Aamir Khan Mastoi: data analysis, writing (review and editing).

Amirul Faiz Rahman: data analysis, writing (review and editing).

Sufian Kamaruddin: data analysis, methodology, investigation.

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Declarations

Conflict of interest The authors declare no competing interests.

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