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PERFORMANCE EVALUATION OF PALM OIL CLINKER AS CEMENT AND SAND REPLACEMENT MATERIALS IN FOAMED CONCRETE

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Abstract. Cellular lightweight concrete (CLC), also known as foamed concrete, has been extensively used in construction for decades. Foamed concrete's properties include low density, excellent thermal conductivity, great workability, and self-compaction; these features enable foamed concrete to be utilized in various contexts. However, the excessive use of conventional materials in concrete production harms the environment. Therefore, using agro-waste as a material to construct ecologically sustainable structures has numerous practical and financial benefits. Palm oil clinker (POC) is a waste product resulting from solid waste combustion during palm oil extraction. This research focused on the properties of foamed concrete with POC at 0%, 25%, 50%, 75%, and 100% as the fine aggregate replacement to develop lightweight foamed concrete (LFC) with a density of 1300 kg/m^3. Besides, the potential of POC powder (POCP) and thermally activated POCP (TPOCP) at 0%, 10%, 20%, and 30% as cement replacements was examined. The development of compressive strength during a 90-day curing period was investigated. In addition, tensile and flexural strengths were assessed and reported, and the elastic modulus of the LFC was discussed. The transport properties of water absorption, porosity, and sorptivity were also investigated. The durability of concrete derivatives can exhibit the product's resistance to chemical attacks and environmental conditions. After 75 days of immersion in hydrochloric acid and magnesium sulfate, the chemical resistivity of the produced LFC was determined by measuring the loss in weight and compressive strength. In addition, the effects of elevated temperatures on the LFC were determined by analyzing the mass loss and compressive strength degradation of specimens exposed to temperatures ranging from 200 to 800 °C. The test results demonstrated that the complete replacement of sand with POC enhanced the compressive strength of LFC by more than 50%. Similarly, POC-based LFC had higher flexural and tensile strengths than normal LFC. Besides, substituting 20% of cement with TPOCP could improve the strength of LFC by 23% during the initial curing days. Utilizing the optimal proportions of POC and POCP could enhance the residual strengths of LFC. Therefore, POC has the potential to be utilized as a fine aggregate and cementitious material to produce sustainable concrete.

Keywords: palm oil clinker, sand replacement material, foamed concrete, durability performance.

Introduction

The highest consumption of ordinary materials, such as fine and coarse aggregates, rocks, water, and cement, is related to the construction sector (Mefteh et al., 2013). The annual consumption of natural aggregates, which accounts for up to 80% of the total volume of concrete mix design, is estimated to be between 8 and 12 billion tons (Bashar et al., 2016; Tu et al., 2006). By 2050, it is expected that the demand for concrete will reach about 7.5 billion cubic meters (Monteiro, 2006), leading to higher consumption of natural resources. Like aggregates and water, worldwide

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cement consumption has been growing (Schneider et al., 2011). The overconsumption of natural resources severely affects the environment, communities, and economy. The overexploitation of natural sand has resulted in its depletion and environmental imbalances (Kumar et al., 2016). World cement production of over 3 billion tons annually (Matos & Sousa-Coutinho, 2012) accounts for roughly 2 billion tons of CO_2, or around 6% to 7% of global CO_2 emissions (Marland et al., 2003). Based on projections, the cement sector will release CO_2 at a rate of more than 3.5 billion tons per year by 2025 (Shi et al., 2011), approximately equivalent to the entire emission in Europe now, and 17% of CO_2 emissions in 2050 are anticipated to come from the cement industry (World Business Council for Sustainable Development & International Energy Agency, 2009). The detrimental repercussions of the overconsumption of natural resources are more concerning in developing countries such as ASEAN, China, India, and Malaysia due to their high rate of construction (Nayaka et al., 2018). Consequently, the application of waste materials in the construction sector has attracted substantial attention in recent years due to their ability to deliver nearly equivalent performance compared to ordinary materials.

Malaysia's agricultural sector has advanced dramatically over the last few decades, with the palm oil industry establishing one of the top three incomes in this tropical country. Malaysia is the second-largest palm oil producer in the world, generating more than half of the world's palm oil annually (Abutaha et al., 2016). This profitable industry produces nearly 3.15 million tons of palm shell waste, which is expected to increase due to the continued worldwide demand for palm oil (Basri et al., 1999). Besides, this industry significantly contributes to Malaysia's pollution problem, producing nearly 3 million tons of solid waste every year. The majority of the waste produced is palm oil clinker (POC) (Basri et al., 1999). POC is a light, solid, and fibrous byproduct of the burning of palm oil shells that has the potential to be used as a lightweight aggregate for concrete when crushed. This abundant waste material has almost no commercial value in Malaysia. Therefore, it can be turned into a viable material for construction. Efforts have been made to include POC as a lightweight aggregate (LWA) to produce lightweight aggregate concrete (LWAC), which can lower the self-weight of concrete without sacrificing much structural strength. In general, lightweight concrete (LWC) may lower the dead load by up to 35% while maintaining structural strength (Omar & Mohamed, 2002). This invention has become a feasible research topic due to the Malaysian government's encouragement of waste conversion (Abutaha et al., 2016; Omar & Mohamed, 2002). Besides, LWC enhances thermal and acoustic insulation, as well as fire resistance, and simplifies the construction process (Lo et al., 2008; Mun, 2007). The production of LWAC requires more cementitious materials, increasing the required energy and construction costs. Around 40% of operating expenditures are associated with energy supply (García-Gusano et al., 2015). POC is composed of 60% pozzolanic silica (SiO_2) and 8% calcium oxide (CaO) (Ahmmad et al., 2014). Therefore, apart from the possibility of substituting POC for natural aggregates, the powdered form of POC has the potential to be employed in place of cement and reduce its high demand in the production of LWAC. Kanadasan and Abdul Razak (2015a) reported that using POC to produce concrete saves costs and energy consumption while lowering carbon emissions. Studies performed on using POC as the aggregate replacement revealed that they might lower the mortar density by 7%, resulting in structural efficiency between 0.035 and 0.05 MPa/kg m^3 (Kanadasan et al., 2015). Abdullahi et al. (2008) conducted a series of trial mixes on POC concrete in order to appropriately analyze the particle size distribution, specific gravity, and water absorption. It was demonstrated that POC aggregate might be used in concrete without any admixture. Kanadasan and Abdul Razak (2014) and Ahmmad et al. (2016, 2017) investigated the mechanical properties of LWC manufactured using POC as the cement and coarse aggregate. Despite substituting half of the POC powder (POCP) for cement, about 70% of the strength of normal mortar may be produced. Besides, the fresh and hardened mechanical properties of self-compacted concrete were affected by the particle packing of POCP.

Lightweight foamed concrete (LFC) has low density, excellent thermal conductivity, workability, and self-compaction, enabling it to be employed in various applications (Just & Middendorf, 2009). Due to its low density and other advantages, foamed concrete is frequently used to manufacture aerated lightweight bricks, pre-cast panels, and excellent heat and thermal insulation. There are several uses for foamed concrete globally; this concrete is quite prevalent in areas hit by housing shortages or prone to harsh weather, such as hurricanes (Mindess, 2019). Annual foamed concrete production is estimated to be between 250,000 and 300,000 m^3 in the United Kingdom and roughly 50,000 m^3 in Canada (Röβler & Odler, 1985). Like conventional concrete, foamed concrete manufacturing utilizes cement and sand, both subject to sustainability and environmental concerns. Therefore, potential alternatives to cement and sand can help mitigate these concerns and make the construction industry more environmentally friendly. Utilizing waste materials as a substitute for foamed concrete components such as cement and sand is one of the most prevalent approaches (Ashish, 2019; Mehta & Ashish, 2020). Wastes from the agricultural (Adhikary et al., 2022a, 2022b; Chinnu et al., 2021; Shah et al., 2021), mining (Shah et al., 2021), industrial (Adhikary & Ashish, 2022; Adhikary et al., 2021a, 2021b, 2021c; Ashish, 2019; Ashish & Verma, 2021; Chinnu et al., 2021; Mehta & Ashish, 2020), and construction (Adhikary et al., 2022b; Rudžionis et al., 2021; Shah et al., 2021) industries can potentially be used in concrete on a global scale. Abraham et al. (2021) aimed to produce LFC by substituting 10% palm oil fuel ash (POFA) for cement and 50% and 100% POC for mining sand (MS). According to reports, POFA and POC are viable options for producing ecological concrete. Chandran (2010) examined the mechanical characteristics of lightweight aggregate foamed concrete produced by POC and found that the chemical resistance and durability of lightweight aggregate foamed concrete against sulfate attacks were better than those of NC. Kanadasan et al. (2015) reported that substituting sand with POC results in concrete with a lower density but comparable strength to conventional concrete. In addition, the carbon emission value of POC was reduced by nearly 10%, indicating that POC has the potential to replace conventional sand. Similarly, Kabir et al. (2017) found acceptable UPV results when POC is substituted for aggregates in concrete mixtures. In another study, Ahmmad et al. (2014) aimed to produce structural LWC by replacing up to half of the natural aggregate volume with POC. It was reported that POC could be used to produce structural LWC with normal to high compressive strengths of between 17 and 54 MPa. In addition to the potential for POC to be used as a replacement for fine and coarse aggregates, it can also be used as a cement substitute material. This is due to the high pozzolanic activity of POC because of the huge quantity of SiO_2 in its chemical composition, as reported by Hamada et al. (2021). The physical characteristics, chemical composition, and scanning electron microscopic (SEM) investigations were conducted to validate the potential of substituting up to half of POC powder (POCP) as a binder and up to 100% of POC as a coarse aggregate (Nayaka et al., 2019). The optimal concentrations of POCP and POC were determined to be 30% and 50%, respectively. A study by Nayaka et al. (2018) demonstrated that substituting up to 40% POCP for cement in cement-lime mortar reduced carbon emissions by more than 30% and reduced costs by 20% without impairing the characteristics of the masonry mortar. Kanadasan and Abdul Razak (2015a, 2015b) demonstrated that approximately 70% of compressive strength was generated when half of the cement was replaced with POCP; the decrease in strength was attributed to the higher silica and reduced amorphous material content of POCP.

The literature evaluation reveals that the feasibility of substituting POC for normal concrete's natural aggregates and cement has been thoroughly investigated. However, information on the use of POC in foamed concrete, particularly as a cement substitute, is limited. In addition, to the best of the authors' knowledge, there is no exploration of the chemical and thermal resistance of POC-based foamed concrete. Therefore, the current study attempts to bridge these gaps in knowledge and study the effects of using POC and POC in LWFC. It aimed to improve the scientific and technical comprehension of the simultaneous utilization of such waste and to contribute to its valorization, as well as to increase the cost-effectiveness and decrease the negative ecological impact of concrete production. With that purpose in mind, this study analyzed the effect of using POC as the sand substitute at replacement levels of 0%, 25%, 50%, 75%, and 100% in LWFC prepared with POCP or thermal-activated POCP (TPOCP) in different replacement ratios of 0%, 10%, 20%, and 30% instead of cement to promote "eco-friendly" constructions. The experimental study evaluated the water transport properties directly influencing POC-based LFC's durability by assessing sorptivity and capillary water absorption. The impact of the utilized waste material on the hardened properties of the produced specimens was studied by analyzing their modulus of elasticity, compressive strength, flexural strength, and splitting tensile strength. In addition, the effects of elevated temperatures on the LFC were examined by analyzing the mass loss and compressive strength deterioration of specimens exposed to temperatures between 200 and 800 °C. Lastly, the chemical resistivity of LFC immersed in hydrochloric acid (HCl) and magnesium sulfate ($MgSO_4$) solutions was evaluated.

1. Experimental work

1.1. Materials

1.1.1. Cement

Type I Ordinary Portland Cement (OPC) with a compressive strength of 42.5 MPa that complies with ASTM C150-14 (American Society for Testing and Materials [ASTM], 2014a) was used for all mixtures. The chemical composition of the utilized OPC is presented in Table 1. Specific gravity, Blaine's specific surface area, and loss on ignition (LOI) of cement were 3.11, 3510 cm^2/gr, and 1.10, respectively. The sieve analysis of cement is illustrated in Figure 1.

Table 1. Chemical compositions of OPC, POC, and TPOCP by weight percentage

Oxide	OPC	POC	TPOCP	ASTM C618-14 (ASTM, 2014b) Class F
SiO_2	14.90	66.3	67.5	
Al_2O_3	3.73	2.77	3.19	
Fe_2O_3	4.67	4.67	5.13	
$SiO_2 + Al_2O_3 + Fe_2O_3$	23.3	73.74	75.82	70 (minimum)
CaO	69	4.43	5.1	
MgO	2.06	4.68	4.72	
Na_2O	0.22	0.22	0.43	
K_2O	0.418	11.5	11.86	
TiO_2	0.454	0.33	0.34	
P_2O_5	0.39	4.44	2.67	
SO_3	4.08	0.66	0.18	5 (maximum)
LOI	1.10	5.11	0.11	12 (maximum)
Specific gravity	3.11	2.2	1.93	
Retained on 45-µm sieve (%)	13.25	21	23	34 (maximum)
Median particle size (µm)	21.28	38.34	36.87	

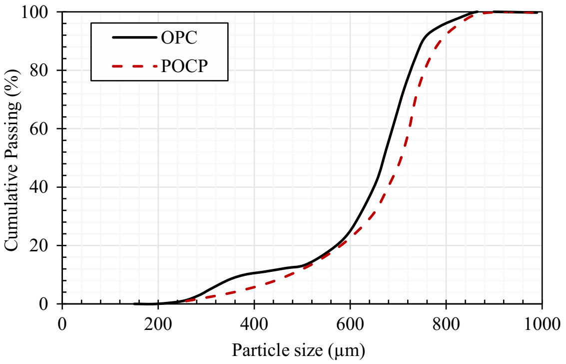


Figure 1. Sieve analysis of cementitious materials

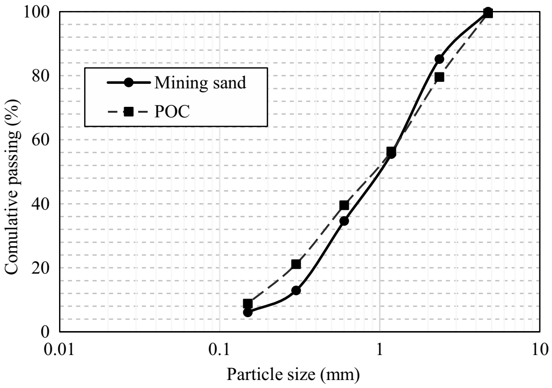


Figure 2. Sieve analysis on POC and MS

1.1.2. Fine aggregate

Palm oil clinker (POC) was collected from a local palm oil factory located in Kuala Lumpur, Malaysia. POC was produced in the boiler by the combustion of palm shell and fiber at temperatures ranging from 100 °C to 800 °C. The fused material was then cooled to room temperature and solidified as pieces of POC with irregular forms. POC particles were crushed using a Los Angeles abrasion machine, sieved with diameters of 4.75 mm, 2.36 mm, and 0.06 mm, and utilized as lightweight fine aggregate in accordance with ASTM C128-14 (ASTM, 2014c) and ASTM C136-14 (ASTM, 2014d). Figure 2 shows the sieve analysis of fine aggregate materials. The physical properties of POC and MS are given in Table 2. Based on BSI Document 92/17688 (British Standards Institution [BSI], 1992), aggregates having a specific gravity of 2.2 or less and a bulk density below 1200 kg/m^3 are categorized as lightweight aggregates. Consequently, POC particles can be considered lightweight structural aggregates. From Table 2, POC fine aggregate has higher water absorption than MS. Therefore, the effects of poor curing of concrete on the hydration process during the initial age can be neutralized when POC particles are used as fine aggregates. This phenomenon has the potential to improve the mechanical properties of hardened concrete made of lightweight POC aggregate.

Table 2. Physical properties of MS and POC aggregates

Properties	MS	POC
Aggregate size	< 4.75 mm	< 4.75 mm
Specific gravity	2.53	2.11
Water absorption (%)	0.42	12
Moisture content (%)	0.1	0.43
Bulk density (kg/m^3)	1295	788

1.1.3. Palm oil clinker powder (POCP)

The study utilized POC collected from a factory, which was then crushed and ground to produce POCP, a cementitious material. POC particles with a size smaller than 4.75 mm were subjected to 30,000 rotations at 150 rpm in a Los Angeles abrasion machine to obtain the POCP. The physical appearance of the generated POPC is shown in Figure 3. The particle size distribution of POCP is shown in Figure 1. Besides, the chemical composition of POCP is presented in Table 1. Like POC particles, POCP is mainly composed of SiO$_2$. The results indicate that the characteristics of POCP met the criteria specified in ASTM C618-14 (ASTM, 2014b), which qualifies it as a suitable supplementary cementitious material (SCM) for use in concrete production. The thermal activation temperature was determined to be 800 °C, and the POCP samples weighing 500 g were thermally activated in silica crucibles in a programmable furnace. The heating pattern D in Figure 5 was used with a heating rate of 10 °C/min to produce thermally activated POCP (TPOCP). This process prevented the formation of unburned carbon and particle agglomeration (Chandara et al., 2012). After three hours of heating, the material was cooled to room temperature at the same rate. The produced TPOCP is shown in Figure 3, and its chemical composition is displayed in Table 1. As shown in Table 1, POCP can be classified as Class-F pozzolan materials based on the total content of SiO$_2$ + Al$_2$O$_3$ + Fe$_2$O$_3$ stated in ASTM C618-14 (ASTM, 2014b). Figure 4 displays the scanning electron microscopy (SEM) of POCP and TPOCP. The results show that POCP had an irregular shape with a porous structure, which was attributed to unburned carbon, as displayed in Figure 4a. In contrast, TPOCP, as shown in Figure 4b, had a significantly reduced porosity due to thermal treatment. The change in morphology of TPOCP compared to POCP was attributed to the removal of unburned carbon during thermal activation.

1.1.4. Foam agent

The foaming agent, Conplast F292 (M), was employed to generate LFC. The foaming agent had a specific gravity of 1.10. The density of foam was determined by dividing the mass of foam by the volume of a container. Numerous trials were performed on the same known volume of the container, and the average density was determined. The ratio of the foaming agent to water was kept at 1:25. The foaming agent and water were placed in the foam generator according to this ratio. The foam generator was connected to the air pressure to produce foam with a density of 50 kg/m^3.

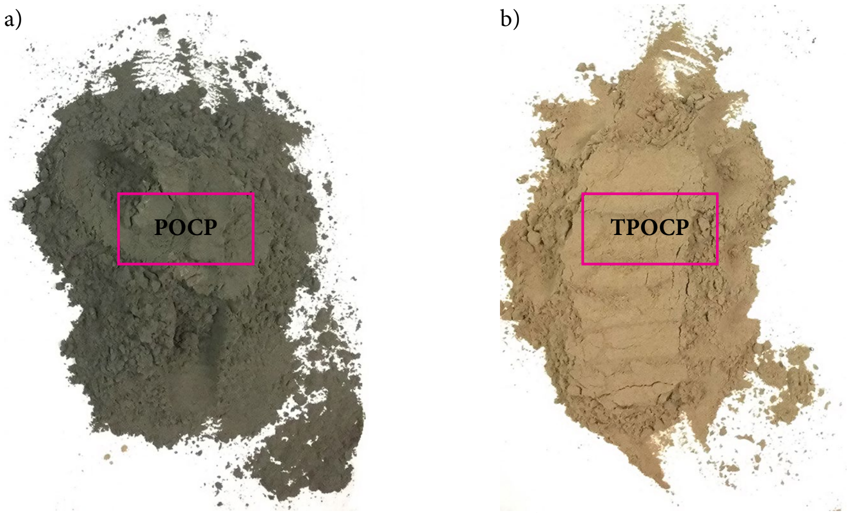
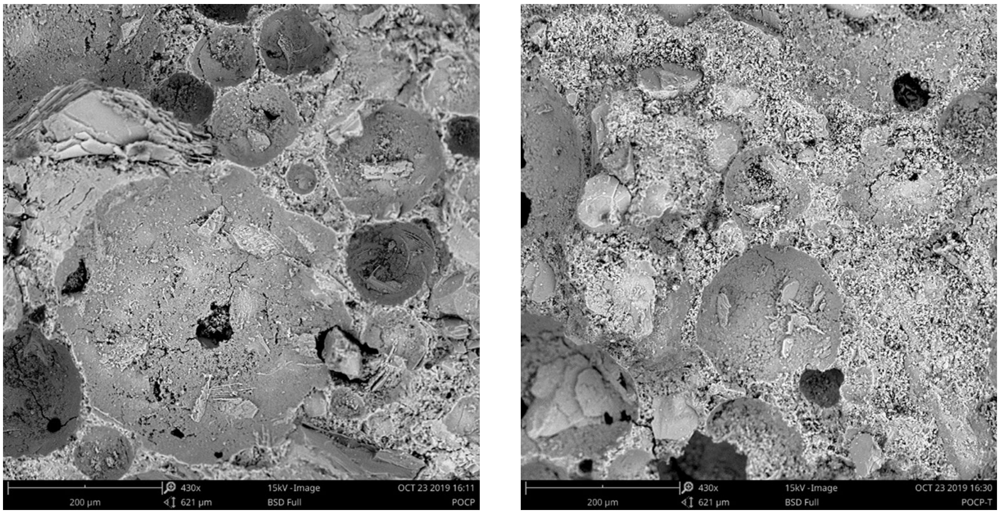


Figure 3. POCP and TPOCP



a) POCP

b) TPOCP

Figure 4. SEM micrographs of POCP and TPOCP

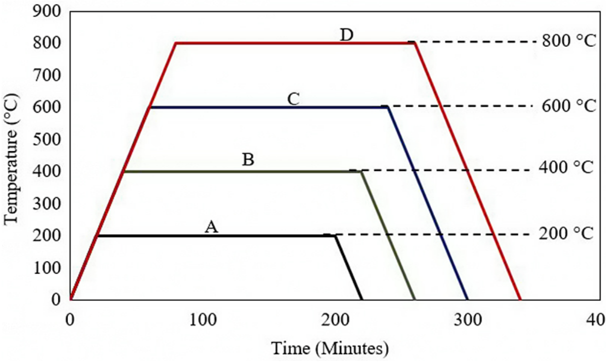


Figure 5. Heating patterns of LFC samples and POCP

2. Mixture proportion

The replacement of MS with POC was performed according to volume replacement because of the porous nature of POC particles. The volume of the MS was calculated and replaced with the equivalent volume of POC using the specific gravity of the sand. POC was used to replace 0%, 25%, 50%, 75%, and 100% of the MS volume. On a mass replacement basis, cement was replaced with POCP or TPOCP. 0%, 10%, 20%, and 30% of the total mass of cement were substituted with POCP or TPOCP. Each specimen was cast at two target densities of 1300 kg/m^3 and 1500 kg/m^3 to assess the influence of the density on the mechanical properties of LFC. A total of 14 mixes were cast for this investigation. Table 3 gives the mix design of the foamed concrete specimens. ASTM C796/C796M (ASTM, 2012a) was used as the guideline for the mix design of specimens. The specimens were designated based on the POCP replacement ratio, the POC replacement ratio, and the target density. For example, the specimen FC-20 (or T20)-100-1300 refers to foamed concrete with a density of 1300 in which 20% of the cement mass was replaced with POCP (or TPOC) and 100% of the MS volume was replaced with POC. As indicated in Table 3, one control mixture was considered for each target density and was labelled as NFC. The w/c ratio and the s/c ratio were taken as 0.45 and 1, respectively. This was determined based on the trial mixes presented in Section 5.1.2.

Table 3. Concrete mix proportion (all units in kg/m^3)

Mix label	Mix proportions									
	Cement			Fine aggregate			Water	w/c	Foam	Density
	% of POCP	POCP	Cement	% of POC	POC	Sand				
NFC-0-0-1300	0	0	522	0	0	522	235	0.45	21	1300
FC-0-25-1300	0	0	522	25	109	391	235	0.45	21	1300
FC-0-50-1300	0	0	522	50	218	261	235	0.45	21	1300
FC-0-75-1300	0	0	522	75	328	130	235	0.45	21	1300
FC-0-100-1300	0	0	522	100	437	0	235	0.45	21	1300
NFC-0-0-1500	0	0	606	0	0	606	273	0.45	16	1500
FC-0-25-1500	0	0	606	25	126	454	273	0.45	16	1500
FC-0-50-1500	0	0	606	50	252	303	273	0.45	16	1500
FC-0-75-1500	0	0	606	75	378	151	273	0.45	16	1500
FC-0-100-1500	0	0	606	100	504	0	273	0.45	16	1500
FC-10-0-1300	10	52	470	0	0	522	235	0.45	21	1300
FC-20-0-1300	20	104	418	0	0	522	235	0.45	21	1300
FC-30-0-1300	30	157	365	0	0	522	235	0.45	21	1300
FC-20-100-1300	20	104	418	100	437	0	235	0.45	21	1300

3. Specimen preparation, curing, and testing

The ingredients were mixed using an ELE-pan mixer set to 50 rev/min. Binders and MS were mixed for approximately 3 minutes to obtain a dry mixture. Following that, water was added to the dry mix, and the mixture proceeded for an additional 2 to 3 minutes. Next, an appropriate amount of foam was added to the mixture to achieve the required density. The mixing continued until the foam and mortar were thoroughly mixed. Once the required densities were achieved, the mixtures were filled in steel cube molds of 100×100×100 mm^3 for the compressive strength test and cylinder molds of 100 mm in diameter and 200 mm in height for the splitting tensile strength test and modulus of elasticity. The prismatic specimens of 75×75×250 mm^3 were utilized for flexural strength tests. The molds were filled in two layers and compacted using the vibrating table for 20 seconds as per BS 1881: Part 125 (BSI, 1986). Plastic sheets were used to cover the molds, and they were left at an ambient temperature of 30 °C±1 for 24 hours. Following that, the specimens were demolded and cured in the water tank until the experiment's predetermined age was reached.

4. Experiment procedures

4.1. Mechanical performance

The effects of substituting POC for fine aggregate and POCP (or TPOCP) for cement on the mechanical characteristics of LFC were examined. The tests included compressive strength, modulus of elasticity, flexural strength, and splitting tensile strength. Compressive strength testing was done in line with BS EN 12390-3:2019 (BSI, 2019) on 100-mm cube specimens. Compressive strength $\left(f_c'\right)$ was measured employing ELE Universal compressive strength machine with a capacity of 250 kN at a space rate of 0.40 kN/s. f_c' was determined as follows:

$$f_c' = \frac{P}{A}, \tag{1}$$

where the term P (kN) denotes the maximum load sustained by the specimen during the test, and A (mm^2) represents the average cross-sectional area of the specimen.

The Young's modulus was calculated in accordance with ASTM C469/C469M-22 (ASTM, 2022) utilizing a compression testing machine and strain measurement equipment. According to Hooke's Law, the relationship between the stress and strain of the concrete is governed by:

$$\sigma = E\varepsilon, \tag{2}$$

in which σ (MPa) is stress, E (MPa) is Young's modulus, and ε is the strain.

The flexural strength test was performed on prismatic specimens in accordance with ASTM C293 (2016). Additionally, the splitting tensile strength test was performed by applying the axial load to cylindrical specimens based on ASTM C469/C469M-22 (ASTM, 2022). All the tests were performed on specimens at the ages of 7, 28, 56, and 90 days. Three specimens with the same mix design were evaluated in each test, and the results were taken as the average of the records.

4.2. Durability tests

4.2.1. Water absorption

The water absorption test was performed on 100-mm cube specimens at the age of 28 days in accordance with ASTM C642-13 (ASTM, 2013) to determine the ability of specimens to absorb water under fixed circumstances with respect to their porosity. The specimens were oven-dried for at least 48 hours at 105±5 °C until their mass remained consistent. Eqns (3) and (4) were used to figure out the water absorption ratio and the volume of the permeable pores, respectively:

$$\text{Water absorption} = \frac{\left(W_B - W_A\right)}{W_A} \times 100\%; \tag{3}$$

$$\text{Volume of the permeable pore space} = \frac{\left(W_C - W_A\right)}{\left(W_C - W_D\right)} \times 100\%, \tag{4}$$

where W_A is the mass of the oven-dried specimen, W_B represents the mass of the surface-dry sample at ambient temperature after immersion, W_C is the mass of the surface-dry sample at ambient temperature after immersion and boiling, and W_D is the apparent mass of the sample in water after immersion and boiling. The density of water ρ_w was 1 g/cm^3.

4.2.2. Sorptivity

The capacity of concrete to absorb and transport water by capillary action can be characterized by measuring the sorptivity of the concrete. Sorptivity was determined as a material property by executing a sorptivity test on 28-day cured disc specimens with a thickness of 50 mm in accordance with ASTM C1585-20 (ASTM, 2020). The LFC samples were oven-dried for 48 hours at 105±5 °C to get a consistent mass. Following that, the samples were allowed to cool to room temperature. Later, the sides of the specimens were covered with plastic tape and placed in the water container. The water level was set 10 mm above the sample to let water penetrate the concrete vertically. At intervals of 1, 4, 10, 20, 30, and 60 minutes, the specimen's weight was recorded. The sorptivity of specimens was calculated using the following expressions:

$$S = \frac{I - A}{\sqrt{t}}, \tag{5}$$

where the term S denotes the rate of water absorption (mm/min$^{(1/2)}$), A (mm^2) is the cross-sectional area of the specimen through which water penetrated, t is the recorded time (min), and I represents the cumulative volume of water absorbed at time t and is governed by:

$$I = \frac{\Delta W}{A\rho_w}, \tag{6}$$

in which ΔW is the difference between the oven dry weight of the cylinder and the weight of the cylinder after 1, 4, 10, 20, 30, and 60 min of capillary suction of water, and ρ_w is the density of water.

4.2.3. Chemical resistivity

The resistance of the concrete derivatives against chemical attacks can be derived from their durability aspects. 100-mm cube specimens were cast and cured for 28 days before being submerged in hydrochloride acid (HCl) and magnesium sulfate (MgSO$_4$). Three specimens were prepared for each period of the experiment, and the average amounts of strength and weight degradation were taken as the results.

4.2.3.1. Acid resistance

Acid resistance testing was carried out based on ASTM C267-01 (ASTM, 2012b) standards. Hydrochloric acid (HCl) at a concentration of 3% was used to determine the specimens' resistance to chemical assault. The weight of each sample was recorded after curing them for 28 days inside the water tank. The acid resistance of specimens was determined by measuring their weight and compressive strength deterioration after immersing them in a 3% HCl solution for 7, 14, 28, 56, and 75 days. The compressive strength degradation and weight loss were determined using Eqns (7) and (8), respectively.

$$\Delta f_c' = \frac{f'_{c(28\,\text{days})} - f'_{c(t\,\text{days})}}{f'_{c(28\,\text{days})}} \times 100, \tag{7}$$

where the term $f'_{c(28\,\text{days})}$ denotes the 28 days compressive strength of the concrete, and $f'_{c(t\,days)}$ refers to the compressive strength of the concrete after immersing for t days in acid solution.

$$\Delta W = \frac{W_i - W_{t\,\text{days}}}{W_i} \times 100, \tag{8}$$

in which W_i refers to the initial weight of the concrete before immersion in acid solution and $W_{t\,days}$ refers to the weight of the specimen after immersing for t days in acid solution.

4.2.3.2. Sulfate resistance

The alkaline nature of concrete makes it vulnerable to chemical attacks caused by sulfuric acid generated from sulfur dioxide present in the air or bacterial processes developed in the sewage system (Singh & Siddique, 2014). Sulfate ions can penetrate the concrete pores, causing corrosion and degradation. The sulfate resistance test was carried out as per ASTM C1012/C1012M-15 (ASTM, 2015). All specimens were immersed in a 5% magnesium sulfate (MgSO$_4$) solution with a PH of between 6 and 8. The solution was replaced every 28 days to assure its effectiveness. The compressive strength of samples was recorded at the ages of 7, 14, 28, 56, and 75 days after immersion in the sulfate solution. The compressive strength degradation was defined by Eqn (7).

4.3. Effect of elevated temperature

The heating patterns, shown in Figure 5, were used to investigate the effect of elevated temperatures on the compressive strength of LFC specimens. The LFCs were subjected to various heating patterns from 28 °C room temperature to 200 °C, 400 °C, 600 °C, and 800 °C, respectively, at a heating rate of 10 °C/min and kept constant for 3 h. The specimens were then cooled down to the ambient temperature at the same pace as they were heated.

5. Results and discussion

5.1. Compressive strength

5.1.1. Effect of fine aggregate size

The compressive strength of the control specimen NFC-0-0-1300, cast with various sizes of MS, namely less than 0.6 mm, 2.36 mm, and 4.75 mm, was examined in order to assess the effect of fine aggregate size on the compressive strength of LFC and to identify the optimal fine aggregate size. The compressive strength development of the investigated specimens is shown in Figure 6. The results indicated that compressive strength could be increased at the same curing age by decreasing the fine aggregate size. In addition, the strength was enhanced by extending the curing period. As shown in Figure 6, the maximum strength was achieved for the specimen cast with a fine aggregate size of less than 0.6 mm at the age of 90 days. The compressive strengths of specimens cast with MS smaller than 0.6 mm were found to be 76% and 52.35% greater than those cast with MS smaller than 4.75 mm and 2.36 mm, respectively. The reason could be attributed to the fact that using smaller fine aggregates can result in pores with a relatively uniform distribution. In contrast, pastes containing larger fine aggregates may have an irregular distribution of pores. This suggests that coarse sand causes bubbles to congregate, forming irregular, big pores. At a given curing age, fine sand causes a more homogenous distribution of bubbles and, consequently, greater strength than coarse sand (Abraham et al., 2021). The findings were consistent with results reported by earlier authors (Nambiar & Ramamurthy, 2006a, 2006b) for foamed concrete with different particle sizes of sand. Therefore, MS passing through a 600 μm sieve was used for the rest of the tests.

5.1.2. Effect of the water-to-cement ratio and sand-to-cement ratio

The water-to-cement (w/c) and sand-to-cement (s/c) ratios affect the compressive strength of concrete. To determine the optimal w/c ratio, the compressive strengths of the control specimen NFC-0-0-1300 were evaluated after 28 days at w/c values of 0.4, 0.45, 0.5, and 0.55, as shown in Figure 7. The test was done using s/c ratios of 1 and 2. As shown in Figure 7, for a given w/c ratio, the compressive strength increased as the s/c ratio decreased. Besides, the compressive strength was enhanced by increasing the w/c ratio when s/c = 2.0. However, when s/c = 1.0, compressive strength was increased by raising the w/c ratio from 0.4 to 0.45, followed by its gradual reduction. When s/c = 2.0, the sand volume was too large, resulting in an insufficient coating of the aggregates with the paste. Consequently, additional water (higher w/c ratio) was employed for lubricating the aggregates, leading to an increase in the compressive strength. This result was contrary to the study of Chan et al. (2018), in which the compressive strength of normal concrete diminished with increasing w/c ratios. The possible explanation was that the compressive strength of hardened cement paste was defined by its pores volume (Kearsley & Wainwright, 2002; Pandey & Sharma, 2000). Chan et al. (2018) reported that the total porosity and capillary pore size reduced as the w/c ratio decreased during the same curing period. However, the current study's direct correlation between compressive strength and w/c suggests that the porosity of specimens decreased as the water content increased. This can be attributed to the increasing influence of the w/c ratio on the hydration products, particularly C-S-H gels, as the curing time increases. In the present study, as w/c ratios increased, porosity decreased, resulting in an increase in compressive strength. This result agreed with the findings of Li et al. (2019), who observed a direct correlation between the w/c ratio, porosity, and compressive strength. The highest compressive strength was attained when the w/c and s/c ratios were set to 0.45 and 1.0, respectively, as shown in Figure 7. Consequently, the remaining experiments were conducted utilizing the optimal ratios of w/c = 0.45 and s/c = 1.0.

5.1.3. The effect of cement replacement with POCP and TPOCP on compressive strength

The compressive strength of concrete is one of the primary concerns when cement is partially replaced by waste materials. Figure 8 compares the compressive strengths of NFC-0-0-1300 with those of LFCs made with POCP as

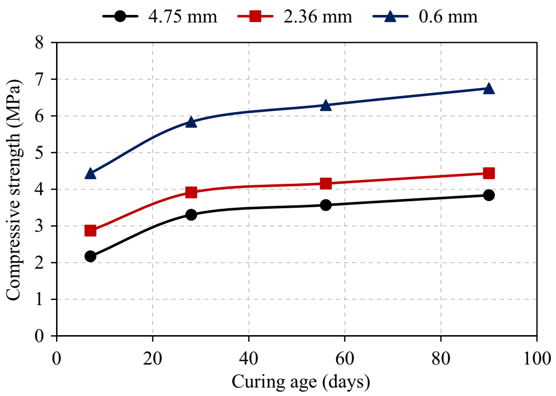


Figure 6. Comparison of the compressive strength of the control specimen cast with different MS sizes

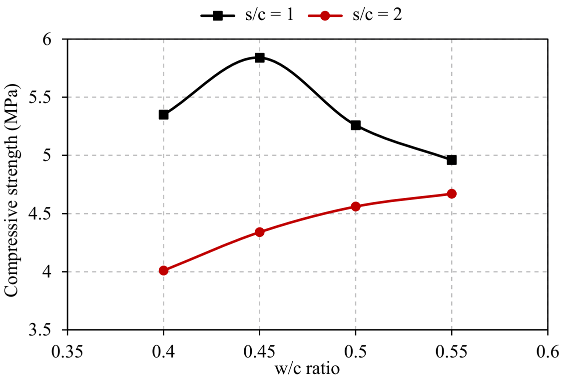


Figure 7. Effects of w/c and s/c ratios on 28-day compressive strength of the control specimen

cementitious material at ages 7, 28, 56, and 90 days. As expected, increasing the curing time increased the compressive strength of specimens for a given POCP concentration. The comparison of the control mixture with specimens containing 20% POCP revealed a slight compressive strength enhancement of less than 1% at all ages. In contrast, the increase in POCP beyond 20% had the opposite effect, as a decrease in compressive strength was observed. The amorphous phase resulting from the pozzolanic activity of POCP could account for the increased compressive strength of LFC when 20% POCP was used as an OPC replacement. In contrast, the dilution impact and postponed beginning of the pozzolanic action of $Ca(OH)_2$ with POCP may account for the decrease in strength observed in this study when 30% of OPC was replaced with POCP. According to Khalil et al. (2014), the dilution effect caused a decrease in $Ca(OH)_2$ generation when POCP substituted 30% of OPC volume. Similarly, Karim et al. (2016a) reported the development of less $Ca(OH)_2$ due to the hydration process when OPC was replaced with POCP at a 30% replacement ratio, resulting in a decrease in the compressive strength of concrete. Moreover, the dilution effect may lower viscosity and impair particle packing (Kanadasan et al., 2015), decreasing the compressive strength of LFC containing 30% POCP. Therefore, it can be concluded from the results that 20% of POCP substitutions for cement attain optimal compressive strength.

The comparison between the compressive strengths of NFC-0-0-1300 and those of LFCs cast with TPOCP as the cementitious material at ages 7, 28, 56, and 90 days is shown in Figure 9. Like the specimens cast with POCP, the compressive strength was enhanced by extending the curing time. In addition, the mixture containing 20% TPOCP in place of OPC obtained the highest compressive strength. Comparing the TPOCP-LFC and POCP-LFC mixtures revealed that the former had higher compressive strengths than the latter. TPOCP was generated by exposing POCP to 800 °C, as described in Section 4.3. Thermal activation of POCP may cause the decomposition of its original compounds, resulting in a decrease in POCP's Total Organic Carbon (TOC). Reduced TOC led to a reduced porosity of POCP particles and an increased inorganic oxide content in TPOCP (Karim et al., 2016b). The reduction in porosity altered the properties of TPOCP-based LFC. TPOCP's less porous particles made the paste denser, which raised the compressive strength of LFC specimens formed with TPOCP compared to those produced by POPC.

Another notable point is the effect of replacing OPC with TPOCP on the compressive strength of LFC at an early age. It was discovered that the development of compressive strength in TPOCP-based LFC at an early age was more significant than at a later age. The 7-day compressive strength of the mix with 20% TPOCP was found to be 23% higher than the control specimen. However, there was only a 4.35% difference between the 20% TPOCP-LFC's 90-day compressive strength and the corresponding control specimen. The remarkable strength growth of TPOC specimens during the early curing days may be attributed to the increased quantities of K_2O and Na_2O content of TPOCP compared to POCP, as indicated in Table 1, which contributed to the rapid development of initial strength (Karim et al., 2016b). Based on the compressive strength results, replacing 20% of the cement mass with POCP or TPOCP was found to be optimal. As a result, the remainder of the experiments were conducted using the optimal replacement ratio of 20% for POCP and TPOCP.

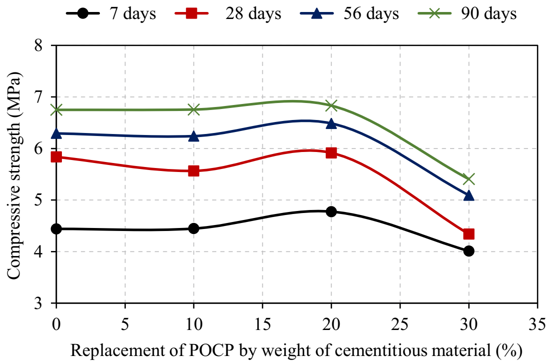


Figure 8. Compressive strength of LFC with POCP as cementitious material

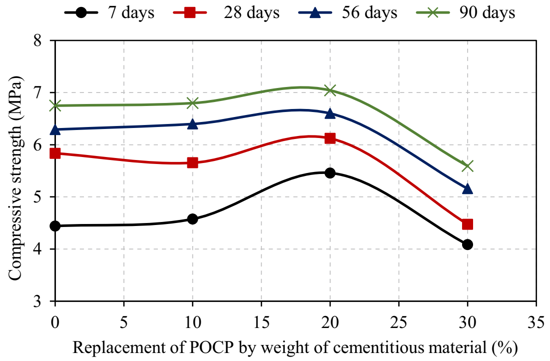


Figure 9. Compressive strength of LFC with TPOCP as cementitious material

5.1.4. The effect of MS replacement with POC on compressive strength

The compressive strengths of NFC-0-0-1300 are compared to those of LFC specimens prepared with POC as fine aggregates aged 7, 28, 56, and 90 days in Figure 10. As indicated in Figure 10, independent of the POC replacement ratio; specimen compressive strength improved with curing age. The compressive strength was increased by substituting fine POC for MS. After being cured for 90 days in the water tank, the compressive strengths of the specimens FC-0-25-1300, FC-0-50-1300, FC-0-75-1300, and FC-0-100-1300 were 25.18%, 41.23%, and 53.67% greater than the control mixture, respectively. As a result, replacing 100% of the MS volume with POC may be preferable. These results were contrary to the studies of Abutaha et al. (2016) and Kanadasan et al. (2018), in which the complete replacement of MS with POC fine aggregate had a negligible effect on the compressive strength of NC. These contradictory findings might be explained by the fact that the kind of concrete and particle size of the POC fine aggregate utilized in this study differ from those employed in earlier studies (Abutaha et al., 2016; Kanadasan et al., 2018). In this paper, the employed POC fine aggregates had a particle size of less than 0.6 mm, whereas the researchers (Abutaha et al., 2016; Kanadasan et al., 2018) used POC fine aggregates with a particle size of 5 mm or less. As shown in Table 2, POC particles possess a lower specific gravity than MS. POC particles with higher fineness may have a better filling feature in concrete than coarser ones. The fine POC filler is believed to contribute to the decrease of internal voids between the POC particles as well as strengthen the bonding between hydrated cement pastes and POC fillers. According to Neville (2009), the volume of holes in concrete affects its strength. The strength of a cement-based mix improves if the volume of voids is reduced. Furthermore, smaller POC particles may result in materials with more significant strengths than bigger ones. Because larger particles are less uniform than small ones, the specimens with larger POC particles had larger holes on the surface and interior. This result was consistent with the study of Darvish et al. (2021), who reported a higher compressive strength for geopolymer concrete with POC fine aggregates with a smaller size than the bigger one. Furthermore, as indicated in Table 2, POC particles absorb more water than MS aggregates. As a result, POC-based LFCs may conserve more internal moisture than control specimens. The fillers' free water might be utilized to hydrate the non-hydrated cement particles, enhancing compressive strength (Haddadian et al., 2023; Lim et al., 2013).

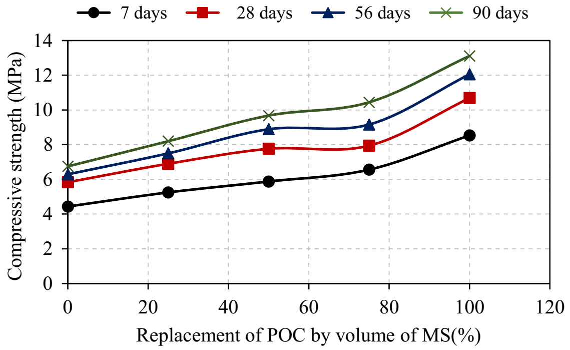


Figure 10. Compressive strength of LFC with POC as fine aggregates

Figure 11 displays the SEM images of the control specimens NFC-0-0-1300, FC-0-100-1300, FC-20-100-1300, and FC-T20-100-1300. It is evident from the images that the control specimens had a high volume of voids in their matrix, as shown in Figure 11a. On the other hand, using POC and POCP in LFC improved the microstructure of the specimens by reducing the internal voids between POC particles, densifying the matrix, and strengthening the bond between hydrated cement pastes and POC fillers, as displayed in Figures 11b–11d. Using TPOCP as a cement substitute led to even denser matrices due to its lower TOC content, as depicted in Figure 11d. These findings were consistent with the impact of POC, POCP, and TPOCP on the compressive strength of LFC.

5.2. Effect of temperature

5.2.1. Effect of temperature on weight loss

Six specimens were selected to observe the effect of elevated temperatures on LFC weight loss. Figure 12 shows the influence of elevated temperature on the weight loss of NFC and LFC with POC, POCP, and TPOCP. As seen in the figure, increasing the temperature resulted in an increase in weight loss for all specimens. At temperatures below 400 °C, weight loss was less than 9%, which might be attributed to restricted free water evaporation and the existence of capillary water. The weight loss increased as the temperature was raised by more than 400 °C. Weight losses of specimen NFC after exposure to temperatures of 400, 600, and 800 °C were 16%, 18%, and 21%, respectively, which were smaller than specimens with 100% POC (22%, 24%, and 27%, respectively). Figure 12 shows that, in contrast to specimens with POC as fine aggregate, no substantial difference was identified between specimens NFC-0-0-1300, FC-20-0-1300, and FC-T20-1300. A similar trend of weight loss increasing with the use of POC as the sand replacement was reported by the authors Jumaat et al. (2015) and Andiç-Çakır and Hızal (2012) for LWC. The weight loss of concrete increases with an increase in the porosity of lightweight aggregates (Andiç-Çakır & Hızal, 2012). During water curing, the water passed from the exterior to the concrete core, and aggregate cavities or air voids absorbed the majority of the water. It should be noted that the aggregates were not completely saturated prior to mixing. After water curing, a 24-hour pre-drying

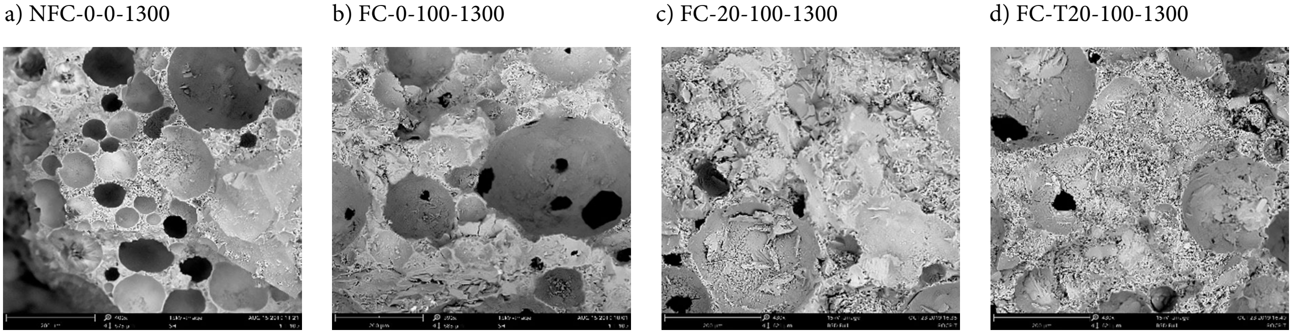

a) NFC-0-0-1300 b) FC-0-100-1300 c) FC-20-100-1300 d) FC-T20-100-1300

Figure 11. SEM images of specimens at 28 days old

step was carried out on the specimens, but bone-drying was not practicable. The samples were then subjected to elevated temperatures. Therefore, the water-filled cavities may have acted as water reservoirs and raised the volume of water that could evaporate.

5.2.2. Effect of temperature on compressive strength

Figure 13 illustrates the effect of elevated temperatures on the compressive strength of the NFC and LFC cast with POC, POCP, and TPOCP. The results indicated that the residual compressive strengths of specimens exposed to temperatures as high as 400 °C did not decrease. In contrast, after 400 °C exposure, the compressive strengths of specimens FC-20-0-1300, FC-20-100-1300, FC-T20-0-1300, and FC-T20-100-1300 were 4.70%, 5.60%, 5.75%, and 4.60% greater than at room temperature. Andiç-Çakır and Hızal (2012) and Sancak et al. (2008) also reported a similar trend for the compressive strength of LWAC exposed to temperatures of 300 °C and 400 °C, respectively. The depletion of water and some chemically mixed water from C-S-H gel and sulphoaluminate hydrates has been attributed to this behavior in the literature (Monteiro, 2006). In addition, exposing concrete to elevated temperatures of between 300 °C and 400 °C could accelerate the hydration reaction (Heikal et al., 2013). The treatment temperature up to around 400°C increased the hydration of cement and the reaction of POC with CH to produce extra hydration products that take up a portion of the available pore, reducing the total porosity of LFC (Heikal et al., 2013; Saad et al., 1996a, 1996b). In contrast, specimens exposed to temperatures exceeding 400°C exhibited a relatively rapid reduction in compressive strength. At 800 °C,

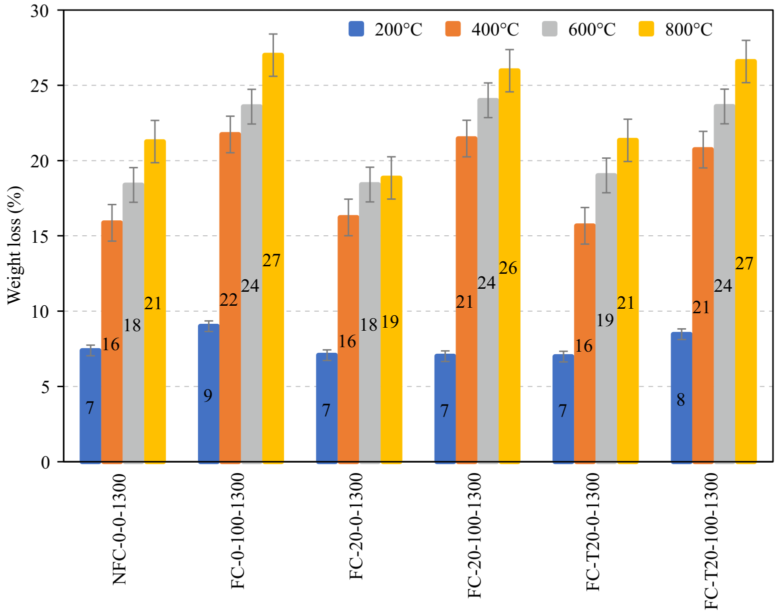


Figure 12. Weight loss of specimens after exposure to elevated temperatures

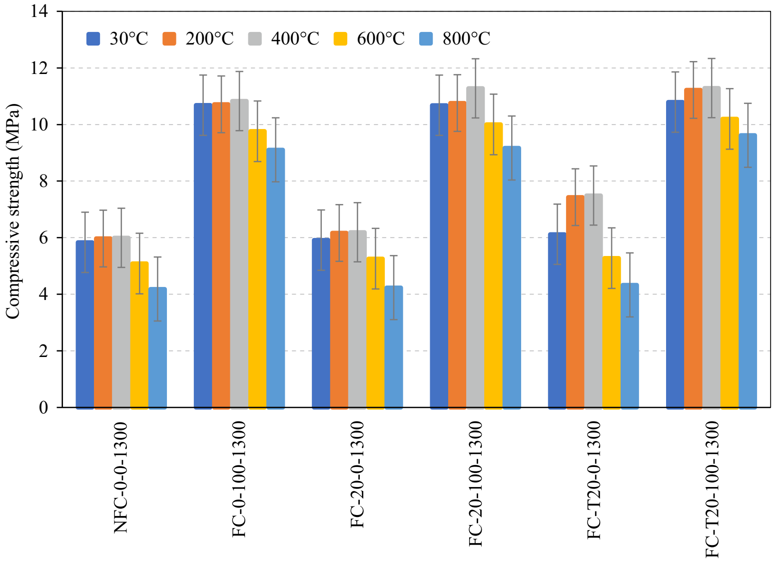


Figure 13. Compressive strength loss of specimens after exposure to elevated temperatures

the compressive strengths of NFC-0-0-1300, FC-0-100-1300, FC-20-0-1300, FC-20-100-1300, FC-T20-0-1300, and FC-T20-100-1300 decreased by 28.26%, 14.76%, 28.38%, 14.15%, 29.24%, and 10.88%, respectively, compared to their counterparts at ambient temperature. It is known that CH and C-S-H, as the hydrated products, are entirely decomposed at an elevated temperature of 800 °C, according to XRD, FTIR, TGA, and FESEM data reported by Amin et al. (2015). Similarly, Saad et al. (1996b) reported an increase in the porosity of cement paste after being exposed to 800 °C due to the development and expansion of microcracks because of the entire thermal degradation of the binding products of hydration, like C-S-H.

Furthermore, $CaCO_3$ decomposed around 800 °C (Heikal et al., 2013), resulting in a significant reduction in compressive strength. This remark is further supported by the developed crack in the cube specimens depicted in Figure 14. The damage induced by high temperatures on concrete can be detected by observing the surface. No substantial damage was noticed on the concrete surface under temperatures of 200 °C and 400 °C, as shown in Figures 14a and 14b, respectively. In contrast, prominent cracks were spread around the surface of the concrete at 600 °C and increased widely at 800 °C, as depicted in Figures 14c and 14d, respectively.

The results demonstrated that as the POC concentration increased, the rate of compressive strength loss at high temperatures decreased, with the FC-T20-100-1300 containing 100% POC and 20% TPOCP replacement ratios exhibiting the least strength degradation when exposed to 800 °C. In general, the decrease in compressive strength of the concrete mixtures examined in this study was consistent with previous research on NC (Li et al., 2012), LWAC (Andiç-Çakır & Hızal, 2012; Sancak et al., 2008), POC-based LWAC (Jumaat et al., 2015), and POCP-based mortars (Haddadian et al., 2023; Karim et al., 2018) exposed to elevated temperatures.

5.3. Tensile and flexural strengths

The splitting tensile, flexural, and compressive strengths of specimens with fresh densities of 1300 kg/m^3 and 1500 kg/m^3 at 28 days are shown in Table 4. As shown in Table 4, tensile and flexural strengths were increased by replacing POC with MS. This result was consistent with the influence of using POC as the MS replacement on the compressive strength of LFC. For the fresh density of 1300 kg/m^3, FC-0-100-1300 showed the highest tensile strength of 1.54 MPa, followed by FC-0-75-1300 with 1.22 MPa, FC-0-50-1300 with 1.10 MPa, FC-0-25-1300 with 0.85 MPa,

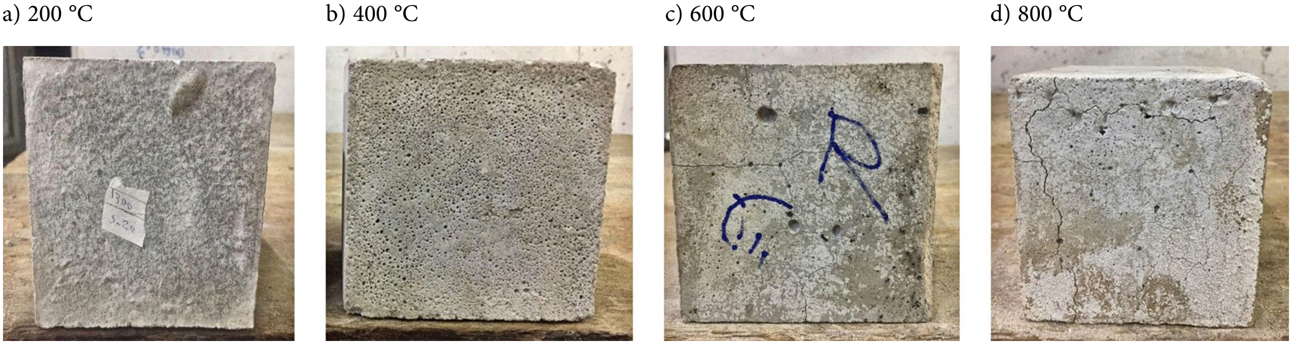

a) 200 °C b) 400 °C c) 600 °C d) 800 °C

Figure 14. The surfaces of specimens subjected to elevated temperatures

Table 4. Splitting tensile strength and flexural strength of specimens

Mix label	28-day splitting tensile strength (MPa)		28-day flexural strength (MPa)		28-day compressive strength (MPa)	
	Fresh density 1300 kg/m^3	Fresh density 1500 kg/m^3	Fresh density 1300 kg/m^3	Fresh density 1500 kg/m^3	Fresh density 1300 kg/m^3	Fresh density 1500 kg/m^3
NFC-0-0	0.83	0.95	1.70	1.95	5.84	6.71
FC-0-25	0.85	0.98	1.86	2.00	6.8	6.95
FC-0-50	1.10	1.89	2.31	4.17	7.76	14.84
FC-0-75	1.22	2.33	2.45	4.99	7.94	17.57
FC-0-100	1.54	2.58	3.07	6.07	10.68	20.70
FC-10-0	0.72	0.85	1.42	1.69	5.88	6.93
FC-20-0	0.83	0.93	1.58	1.82	5.91	7.00
FC-30-0	0.52	0.63	1.24	1.50	4.34	6.74
FC-T10-0	0.73	0.88	1.57	1.84	5.92	7.01
FC-T20-0	0.86	0.97	1.82	2.06	6.12	7.16
FC-T30-0	0.53	0.66	1.36	1.75	4.47	7.03
FC-20-100	1.38	2.69	2.87	5.50	10.68	20.71
FC-T20-100	1.50	3.08	3.05	6.70	10.80	21.88

and control NFC-0-0-1300 with 0.83 MPa. The effect of POC as the fine aggregate on flexural strength followed a similar pattern. POC particles might lead to an increase in the generation of C-S-H gel and reduced unreacted hexagonal plates like calcium hydroxide in LFC as compared to normal foamed concrete with MS. Muthusamy et al. (2021) found C-H-S to be abundant in the concrete cast with POC as fine aggregates, indicating the occurrence of a pozzolanic reaction between POC fine aggregates and calcium hydroxide, a by-product from cement hydration, resulting in the development of extra C-S-H gel. In addition, the POC aggregates might potentially fill in the holes, leading to pore refinement and, therefore, a denser and stronger LFC structure. Similar results were observed by Ahmmad et al. (2017), in which using POC as fine aggregates led to an increase in the splitting and tensile strength of LWAC.

The substitution of POCP or TPOCP for OPC had a minor effect on the splitting tensile strength of specimens. As shown in Table 4, there was no discernible difference in the splitting tensile strengths of FC-20-0-1300 and control NFC-0-0-1300, while FC-10-0-1300 and FC-30-0-1300 had splitting tensile strengths of 0.72 MPa and 0.52 MPa, respectively, which were slightly less than control NFC-0-0-0.83 with 0.83 MPa. Concrete's tensile strength is predominantly determined by the characteristics of the cement paste and the bond strength between the aggregate and cement paste. Although using POCP in concrete can increase its compressive strength, it may not affect the concrete's tensile strength (Sata et al., 2007). POCP is a pozzolanic material that can react with calcium hydroxide in the presence of water to produce extra C-S-H, contributing to the concrete's strength and durability. However, POCP may have a limited influence on the bond strength between the aggregate and the cement material. This is due to the fact that the bond strength is primarily determined by the interfacial transition zone (ITZ) between the aggregate and cement paste, which is a small region in which the aggregate and cement paste contact. The ITZ depends on the cement material's quality and the aggregate's surface properties. While POCP can enhance the overall quality of the cement paste, it may not inherently enhance the surface features of the aggregate or the bond strength between the aggregate and cement paste (Alengaram et al., 2013). Consequently, applying POCP may not significantly impact concrete's tensile and flexural strengths. The optimal tensile and flexural strengths were reached by replacing POCP or TPOCP for 20% of the cement. At the same replacement ratio, TPOCP specimens had marginally higher tensile and flexural strengths than POCP specimens.

Another point is the effect of concrete density on the strengths. It can be observed from Table 4 that tensile, flexural, and compressive strengths were enhanced by increasing the fresh density of the specimens. Several factors account for the correlation between the density and strength of concrete. Firstly, increasing the concrete density can increase the proportion of solid particles, thereby increasing the contact area between the particles and the cement material. This enhanced contact area can increase the interlocking and bond strength between particles and paste, increasing concrete's compressive strength (Mindess et al., 2003; Neville & Brooks, 2010). Secondly, an increase in the density of concrete can reduce the material's porosity. The existence of voids in concrete may operate as vulnerable points and generate stress concentrations, resulting in decreased flexural and tensile strengths. By minimizing pores in concrete, the material becomes more homogeneous and can withstand stresses and forces more efficiently, resulting in increased flexural and splitting tensile strength (Monteiro, 2006; Neville & Brooks, 2010). According to ASTM C330, the minimum 28-day tensile strength of LWC for structural consideration is 2.0 MPa. Therefore, sustainable structural LFC members with a fresh density of 1500 kg/m^3 can be designed by substituting 20% POCP or TPOCP for cement and at least 75% POC fine for MS.

The relationship between tensile and flexural strengths and the compressive strength of specimens is illustrated in Figure 15. According to Narayan and Ramamurthy (2000), it is reasonable to assume that the factors affecting compressive strength also impact tensile strength, and vice versa. Additionally, it was discovered that, on average, the improvement in tensile strength growth followed a similar pattern and exhibited a linear relationship with the increase in compressive strength (Abraham et al., 2021). Figure 15 gives rise to the fact that the improvement in compressive strength resulted in an improvement in splitting tensile strength and flexural strength. As seen in the figure, the slope of the splitting tensile strength was less than the flexural strength. Thus, it can be concluded that the rate of increase in flexural strength was higher than the rate of increase in splitting tensile strength, and the enhancement effect of POC and POCP in LFC was more pronounced on flexural strength than on tensile strength. Based on the results shown in Figure 15, the relation-

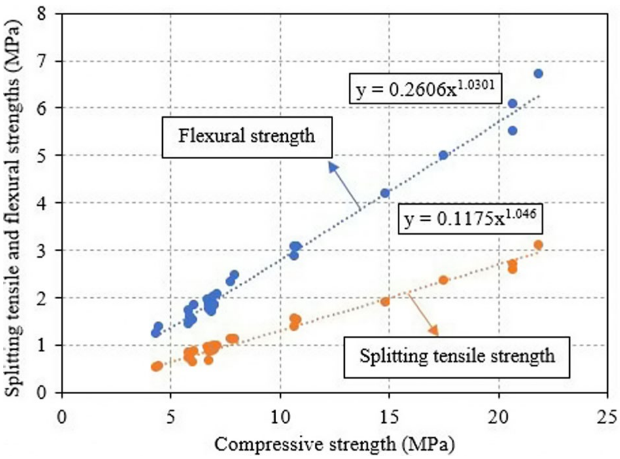


Figure 15. Relationship of tensile and flexural strengths with the compressive strength of LFC with POC as fine aggregate and POCP or TPOCP as cementitious materials

ship between the flexural strength $\left(f_b\right)$ and compressive strength $\left(f'_c\right)$ of LFC is governed by:

$$f_b = 0.2606\left(f'_c\right)^{1.03}. \tag{9}$$

Besides, the relationship between the splitting tensile strength $\left(f_t\right)$ and compressive strength $\left(f'_c\right)$ of LFC can be expressed as:

$$f_t = 0.1175\left(f'_c\right)^{1.046}. \tag{10}$$

5.4. Modulus of elasticity

Concrete's modulus of elasticity (MOE) significantly influences its mechanical performance. The Young's modulus of a material is a property that impacts its stiffness, and the MOE of most materials is constant during the early loading period. The MOE of concrete is governed by the mechanical properties of its constituent components and their proportions in the mix design. Table 5 shows the modulus of elasticity of specimens (MOE) and their corresponding cube compressive strength (f'_{cu}). There was a direct correlation between the compressive strength of concrete and its MOE, with an increase in compressive strength leading to an increase in MOE. As shown in Table 5, the MOE of the control specimen was 5.05 MPa, whereas it increased by 1.19%, 24.16%, 35.64%, and 45.54% when 25%, 50%, 75%, and 100% of the MS was replaced with POC fine aggregates. In addition, the MOE values of specimens FC-25-100-1500 and FC-T25-100-1500 were marginally higher than the MOE values of specimen NFC-0-100-1500. Therefore, the use of POC and POCP (or TPOCP) in LFC can increase its MOE. POC-based LWC was found to have a higher compressive strength than the control specimen. This high strength could contribute to the stiffness of the concrete, as the interparticle bonding between the POC particles and the cement paste was enhanced (Muthusamy et al., 2021), resulting in a higher modulus of elasticity. The high stiffness of POC was attributed to its dense and compact structure, which is primarily composed of silica and alumina. In addition, using POC as fine aggregates could enhance the microstructure of the concrete, especially at ITZ between the aggregates and cement material (Alengaram et al., 2013; Bentz & Snyder, 1999; Lo et al., 2007). The high surface area of the POC particles could improve the distribution of the cement material, resulting in a more uniform and denser microstructure. This, in turn, could contribute to an increase in the concrete's modulus of elasticity.

According to Table 5, the MOE is proportional to the concrete's compressive strength and density. The following expression can be used to determine the MOE of LFC:

$$E_{s,pre} = 6\times\left[\left(\frac{\rho}{2400}\right)^2 \times \left(f'_{cu}\right)^{\frac{1}{3}}\right], \tag{11}$$

in which $\rho\left({}^{\text{kg}}\!/_{\text{m}^3}\right)$ is the air-dry density of the concrete, and $f'_{cu}\left({}^{\text{N}}\!/_{\text{mm}^2}\right)$ is the cube compressive strength of the concrete. The ratios of the MOE obtained from the experimental tests-to-the predicted ones $\left(\frac{E_{s,(exp)}}{E_{s,pre}}\right)$ indicate that Eqn (11) leads to a good prediction of the MOE of LFC with POC as fine aggregate and POCP (or TPOCP) as cementitious materials.

5.5. Water absorption

Water absorption and permeable void test findings for specimens NFC-0-0-1500, FC-0-100-1500, FC-20-100-1500, and FC-T20-100-1500 are presented in Table 6. Additionally, Figure 16 illustrates the rate of water absorption over time. The water absorption rate of concrete over time can provide information regarding its capillary sorptivity and durability. The results indicated that NFC-0-0-1500 absorbed the least water compared to specimens in which 100% of the MS was replaced with POC fine aggregate. As shown in Table 6, the water absorption of the control specimen NFC-0-0-1500 was 18.22%, while it increased to 22.80% in the specimen FC-0-0-1500, which was 25.14% higher than the control specimen. As depicted in Figure 16, the trends in the water absorption rate of specimens over time were comparable to the water absorption test results presented in Table 6. The lowest rate was found in the control sample NFC-0-0-1500, while the rate increased when MS was replaced with POC fine aggregate. For specimens FC-20-100-1500 and FC-T20-100-1500, however, a slight

Table 5. Elastic modulus of the concrete

Mix label	Air-dry density, $\rho\left({}^{\text{kg}}\!/_{\text{m}^3}\right)$	28-day Compressive strength, f'_{cu} (MPa)	Modulus of elasticity, $E_{s,(exp)}$ (MPa)	Predicted modulus of elasticity, $E_{s,pre}$ (MPa)	$\frac{E_{s,(exp)}}{E_{s,pre}}$
NFC-0-0-1500	1563	6.71	5.05	4.80	1.05
FC-0-25-1500	1585	6.94	5.11	5.00	1.02
FC-0-50-1500	1603	14.87	6.27	6.58	0.95
FC-0-75-1500	1615	17.57	6.85	7.06	0.97
FC-0-100-1500	1635	20.70	7.35	7.64	0.96
FC-25-100-1500	1655	21.50	7.52	7.93	0.95
FC-T25-100-1500	1685	22.00	7.88	8.29	0.95

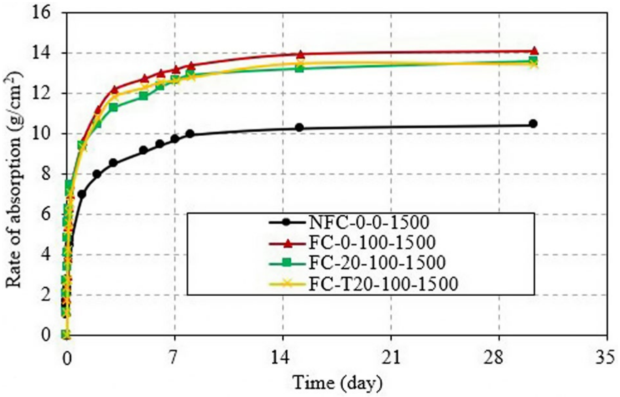


Figure 16. The effect of POC, POCP, and TPOCP on the water absorption of the foamed concrete

Table 6. Water absorption and permeable voids of specimens

Specimen label	Water absorption (%)	Porosity (%)	Compressive strength (MPa)
NFC-0-0-1500	18.22	39.55	6.75
FC-0-100-1500	22.80	41.76	20.83
FC-20-100-1500	22.42	41.06	20.89
FC-T20-100-1500	22.53	40.81	21.77

reduction was observed compared to specimen FC-0-100-1500. The reason could be attributed to the porous structure of POC fine particles (Mundra et al., 2020). As presented in Table 6, the higher porosity of POC compared to MS increased the porosity of the specimens. However, using POCP or TPOCP as cementitious materials reduced the water absorption of the LFC. Using POCP or TPOCP in place of cementitious material could improve the pozzolanic activity of the concrete and generate additional C-S-H gel to fill in the pores in the concrete (Karim et al., 2016a). Similar results were reported by Karim et al. (2016b), who investigated the influence of POCP and TPOCP on the water absorption of LWC.

5.6. Chemical resistance

The durability of concrete can be used to signify the product's resistance to chemical assaults and weathering conditions. To study the chemical resistance, 100-mm cube specimens were immersed in chemical solutions for 7-, 14-, 28-, 56-, and 75-day periods. Before immersing the cubes in the acid, their weight, size, and physical appearance were documented to monitor any possible changes resulting from the chemical assault. Figures 17 and 18 depict the physical states of control NFC-0-0-1500 and FC-0-100-1500 after 28 days of submersion in HCl and $MgSO_4$ solutions. As seen in the figures, a minor discoloration occurred on the surface of both the control and FC-0-100-1500 specimens, and the edges were damaged during solution immersion. However, no signs of erosion were found.

a) NFC-0-0-1500

b) FC-0-100-1500

Figure 17. Appearance investigation after 28 days of immersion in HCl

a) NFC-0-0-1500

b) FC-0-100-1500

Figure 18. Appearance investigation after 28 days of immersion in $MgSO_4$

The compressive strength development of the specimen after immersion in water, HCL, and MgO4 solutions is given in Table 7. According to Table 7, increasing the immersion time enhanced the compressive strength of water-cured specimens. The rate of strength increase with curing age was found to be greater in specimens containing 100% POC as the sand replacement than in the control specimen NFC-0-0-1500. As shown in Table 7, the compressive strength of specimen NFC-0-0-1500 at 75

Table 7. Compressive strengths of specimens after immersion in solutions (Unit: MPa)

Specimen label	Water					HCl					MgO_4				
	7 days	14 days	28 days	56 days	75 days	7 days	14 days	28 days	56 days	75 days	7 days	14 days	28 days	56 days	75 days
NFC-0-0-1500	6.0	6.05	6.75	7.36	7.55	5.80	5.81	6.04	5.75	5.14	6.05	6.19	6.93	7.25	7.33
FC-0-100-1500	15.6	17.26	20.83	25.64	26.25	14.82	15.05	15.75	16.12	14.21	15.89	17.88	22.06	26.03	26.1
FC-20-100-1500	15.8	17.3	21.0	25.9	26.4	15.5	16.2	18.0	19.7	17.2	15.9	17.7	21.7	26.6	26.5
FC-T20-100-1500	15.9	17.4	21.8	26.2	26.5	15.6	16.2	18.9	20.1	17.5	16.1	18.0	22.9	27.1	26.8

days was 25.83% greater than at 7 days, while the compressive strength of specimens with 100% POC as sand replacement increased by an average of 67.35% over the same curing period. The higher strength development of POC-based specimens compared to the control specimen could be due to the internal curing effect. Since POC fine absorbs more water than conventional aggregate, it may contribute self-curing properties to the ITZ at later ages. During the early stages of the casting process, the POC fine aggregates absorbed the water introduced to the cement material. Once the cement hydration process commenced, the ITZ was resupplied with localized water (Bentz & Snyder, 1999; Lo et al., 2007), leading to the higher strength development of POC-based LFC than the control specimen.

As shown in Table 7, both the control and POC-based LFC specimens' compressive strengths increased steadily until 56 days of immersion in HCL solution, after which they decreased. The 75-day compressive strength of the control specimen was nearly 11.40% lower than its 7-day strength, whereas only 4.12% of strength degradation was detected in the specimen FC-0-100-1500 with 100% POC as the sand replacement. In contrast, the 75-day compressive strengths of FC-20-100-1500 and FC-T20-100-1500 specimens were approximately 11% and 12.2% greater than the 7-day values, respectively. The acid-attacked cement matrix decomposes primarily due to calcium release from the hydration products, with aluminum and iron release occurring only at low pH levels (Gutberlet et al., 2015). The C-S-H structure with a high CaO/SiO_2 ratio is more susceptible to acid attacks, whereas the C-S-H structure with a low CaO/SiO_2 ratio decomposes more slowly (Bassuoni & Nehdi, 2007). In addition, the mixture's chemical composition and CaO/SiO_2 ratio are critical elements in determining the acid attack's impact (Chatveera & Lertwattanaruk, 2011). Due to its crystalline structure and low calcium content, C-S-H with a low CaO/SiO_2 ratio is less susceptible to decomposition (calcium release) (Alnahhal et al., 2018). These support the findings of this investigation, which demonstrated excellent durability against chemical assault for POC-based LFC with low CaO/SiO_2 ratios.

The relative residual strength of specimens immersed in HCL solution over the immersion age is shown in Figure 19. As depicted in Figure 19, the compressive strengths of specimens immersed in HCL were generally lower than those of water-cured specimens for a given curing time. Replacing the whole sand aggregates with fine POC led to the least residual strength of LFC. As illustrated in Figure 19, the compressive strengths of control specimen NFC-0-0-1500 submerged in HCL solution for 7 days, 14 days, 56 days, and 75 days were 3.33%, 4.00%, 10.52%, 21.88%, and 31.92% less than those immersed in water, respectively. The compressive strengths of POC fine specimen FC-0-100-1500 submerged in HCL solution were 5.00%, 12.80%, 24.40%, 37.13%, and 45.88% lower than those immersed in water after 7, 14, 28, 56, and 75 days, respectively. However, replacing 20% of the OPC with POCP or TPOCP could improve the acid resistance of the specimen FC-0-100-1500. As illustrated in Figure 19, the strength degradation of FC-20-100-1500 and FC-T20-100-1500 specimens immersed in HCL for 7-, 14-, 56-, and 75-day periods was approximately 1.89%, 6.5%, 14.3%, 23.93%, and 34.8%, respectively, which was comparable to the results observed for the control specimen. The results were consistent with the influence of POC, POCP, and TPOCP on the water absorption of LFC, discussed in Section 5.5. The primary explanation for POCP and TPOCP effects on specimen acid resistance may be an amorphous phase that is reactive based on the pozzolanic activity, forming the C-S-H gel for the development of strength, resulting in a compact structure, and therefore increasing durability (Karim et al., 2016a). Besides, TPOCP's effect on specimen acid resistance may be related to the decrease in TOC caused by substituting TPOCP for cement. The decreased TOC causes a decrease in particle porosity and an increase in TPOCP's inorganic oxide content (Karim et al., 2016b). Reduced porosity influences the matrix characteristics of mortar. The less porous TPOCP particles in the paste make it denser, increasing the acid solution permeability of concrete.

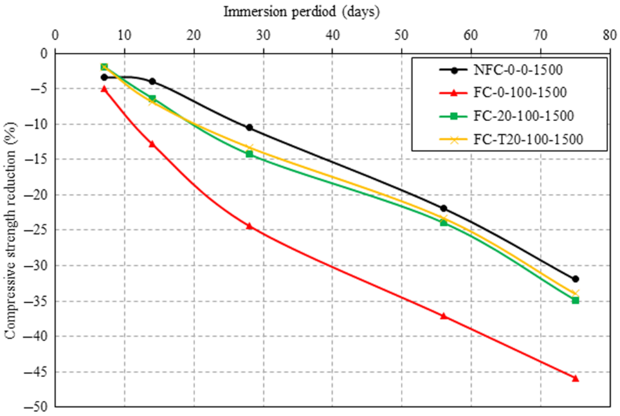


Figure 19. The strength variation of specimens immersed in HCL solution

The relative residual strength of specimens immersed in $MgSO_4$ solution over the immersion age is shown in Figure 19, in which the loss of strength is indicated by negative values and vice versa. As shown in Table 7 and Figure 20, the compressive strength of specimens was slightly raised after 28 days of immersion in MgO4 solution and then decreased. After 28 days of immersion, the compressive strength of the control specimen NFC-0-0-1500 increased by 2.7%, whereas the compressive strength of the specimens containing POC and POCP (or TPOCP) increased by 3.33% to 5.90%, respectively. A comparison of results indicates that the compressive strength of NCF-0-0-1500 decreased by 2.9% after 75 days of immersion, whereas the compressive strength of FC-0-100-1500 decreased by less than 1%. In contrast, after 75 days, the compressive strengths of FC-20-100-1500 and FC-T20-100-1500 specimens were comparable to those of their water-cured counterparts. The influence of substituting MS with POC and OPC with POCP or TPOCP on the chemical resistance of LFC was consistent with the mass loss of specimens represented in Table 8. As shown in Table 8, the weight of the specimens decreased after immersion in the HCL solution. The control specimen NFC-0-0-1500 lost 5.27% of its weight after 75 days, while the specimen FC-0-100-1500 lost 8.4%. When 20% of OPC was replaced with POCP and TPOCP, the weight loss of specimens FC-20-100-1500 and FC-T20-100-1500 was marginally reduced, resulting in weight losses of 6.54 and less than 6.00%, respectively.

Clearly, POC, POCP, and TPOCP mitigated the detrimental effects of the MgO_4 solution on the strength of concrete. In addition, the superficial increase in compressive strength observed after 28 days of exposure to MgO_4 solution could be because of the generation of ettringite, which led to a more closed pore structure and a slight improvement in compressive strength. This was also confirmed by Jo et al. (2017), who indicated that the existence of more voids in the porous structure of the cement matrix enabled the expansive ettringite to be accommodated over the initial period of immersion. Because of the continuous production of ettringite, which has a relatively high volume, internal cracks were formed due to the constant expansion, resulting in a decrease in compressive strength after 75 days of immersion. Alnahhal et al. (2018) observed a similar phenomenon when they discovered that the compressive strength of specimens immersed in an aggressive sulfate solution increased with a curing time of up to 28 days but decreased after 120 days. Due to the pozzolanic reaction, which limits the diffusion of sulfate ions throughout the cement matrix, applying POCP (or TPOCP) as the cement replacement can reduce the decalcification of hydration products.

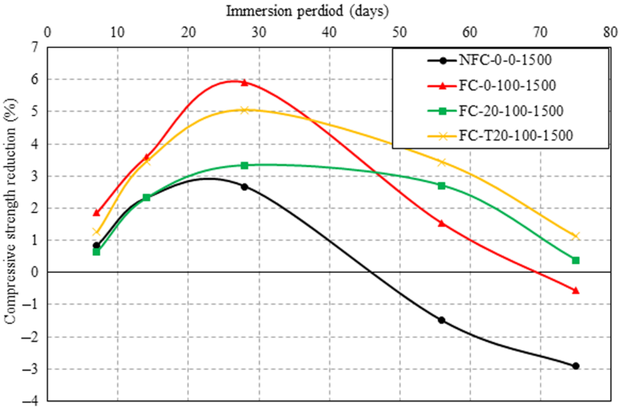


Figure 20. The strength variation of specimens immersed in MgO_4 solution

5.7. Application and prospect

Given their abundance in tropical countries, as well as their chemical composition and adequate fineness, POCs have been shown to possess high pozzolanic reactivity (Karim et al., 2016a). This property enables POCs to refine pores and enhance the compressive strength of foamed concrete. As a result, POCs can be effectively utilized as a replacement for cement or fine aggregate. In addition to their pozzolanic reactivity, POC particles also possess a porous structure that makes them more lightweight than conventional materials. This property is especially beneficial when POC is used as an aggregate in foamed concrete applications where low density is desired. By incorporating fine POC and POCP (or TPOCP), foamed concrete with a low density and sufficient compressive strength can be produced. Such foamed concrete is suitable for non-load-bearing applications such as flooring and wall panels. By doing so, POCs can provide a cost-effective and environmentally sustainable solution to produce lightweight and durable concrete.

Meeting the low strength requirements for non- and semi-load-bearing applications in foamed concrete products is achievable (Mugahed Amran et al., 2016; Shah et al., 2021). Therefore, incorporating POC and POCP (or TPOCP) in foamed concrete is a more appealing option compared to traditional concrete. With normal concrete,

Table 8. Weights of specimens after immersion in solutions (Unit: gr)

Specimen label	Water					HCl					MgO_4				
	7 days	14 days	28 days	56 days	75 days	7 days	14 days	28 days	56 days	75 days	7 days	14 days	28 days	56 days	75 days
NFC-0-0-1500	1560.03	1581.20	1593.10	1600.07	1600.97	1561.57	1552.93	1534.23	1506.73	1479.23	1552.37	1555.37	1572.47	1596.57	1602.03
FC-0-100-1500	1578.73	1585.97	1601.67	1607.73	1613.67	1547.27	1524.67	1508.80	1463.73	1418.00	1585.07	1604.07	1642.20	1651.20	1600.97
FC-20-100-1500	1579.23	1583.33	1593.43	1600.20	1609.07	1568.23	1535.57	1516.97	1482.70	1465.67	1573.33	1574.10	1596.83	1587.00	1595.93
FC-T20-100-1500	1552.43	1575.17	1591.47	1599.53	1603.30	1541.87	1533.93	1512.67	1475.53	1449.87	1555.13	1575.37	1577.90	1585.37	1595.73

it is typically necessary to achieve significant compressive strength, usually exceeding 20 MPa, for it to be used. Furthermore, since conventional concrete is used in structural components and for load-bearing purposes, end-users may be less accepting of waste materials being used in it. Waste materials usually have a negative impact on the fresh properties and workability of concrete due to their porous nature and particle shape, leading to increased water demand (Shah et al., 2021). This was observed in previous studies by the authors (Alengaram et al., 2013; Kupaei et al., 2013; Shafigh et al., 2013). However, this issue can be addressed by the workable nature of foamed concrete and the use of chemical admixtures like superplasticizers if necessary. Foamed concrete is typically more workable than normal concrete, making it a more practical option for incorporating waste materials. In normal concrete, incorporating waste materials, especially at high volumes, can significantly affect workability, leading to additional costs for chemical admixtures and possibly requiring changes to the mix proportions. In contrast, waste materials can be incorporated directly into foamed concrete mixes without significant changes to the mix proportions.

Despite the difficulties associated with waste material incorporation, foamed concrete is gaining popularity in the construction industry because of its distinctive characteristics, such as reduced density, thermal conductivity, and cost. There are numerous applications for foamed concrete, such as lightweight slabs, precast panels, and thermal and acoustic insulation. The yearly market for foamed concrete in the United Kingdom is projected to be between 250,000 and 300,000 m^3, while in Canada and South Korea, it is between 250,000 and 300,000 m^3 and 50,000 m^3, respectively (Amran et al., 2015). In the Middle East, foamed concrete can be used to lessen the adverse effects of temperature fluctuations. The worldwide market for foamed concrete was anticipated to increase by 4.4% per year from 2016 to 2022 and reach $458.1 million by 2022 (Shah et al., 2021), demonstrating its future potential.

Numerous nations are implementing efforts to encourage sustainability in the construction sector, including minimizing material usage, optimizing material resources, reducing CO_2 emissions, and limiting waste. These initiatives comprise the Green Building Index in Malaysia, the Green Building Evaluation Standard in China, the Sustainable Singapore Blueprint in Singapore, the Comprehensive Assessment System for Built Environment Efficiency in Japan, the Taiwan Green Building Manual in Taiwan, the Code for Sustainable Homes in the United Kingdom, and the Leadership in Energy and Environmental Design in the United States. Furthermore, it is possible that waste materials will become less expensive than cement and sand in the future, as the latter materials may experience price increases due to environmental factors. For example, global cement production in 2017 was approximately 4.1 billion tons (Singh et al., 2017), and each ton of cement produced emits roughly 0.9–1.0 tons of CO_2 (Ali et al., 2011; Zhang et al., 2014). To accomplish a 50% reduction in these CO_2 emissions via carbon capture approaches, the cost would rise by approximately 55% (Ali et al., 2011). In addition, sand, which is commonly used as a fine aggregate in construction, is a non-renewable material that some countries rely on imports for. In 2014, global sand imports totaled $2.09 billion, with the top three importers being Singapore, Canada, and Belgium-Luxembourg (Gavriletea, 2017). This rising demand for high-quality sand may ultimately result in a price increase. Consequently, utilizing waste materials as substitutes for cement and sand may be an economically viable option in the future, as cement and sand prices may continue to rise due to environmental factors. Moreover, foamed concrete building components offer the advantage of lower construction, production, and transportation costs, with savings of approximately 10–20%, as demonstrated by research (Amran et al., 2015). The lightweight characteristics of most waste materials, such as POC, can also result in foamed concrete products with reduced density, making it easier to handle individual components, increasing labor efficiency, and further contributing to cost and time savings in construction projects.

Conclusions

According to the experimental tests performed in this study, the following conclusions were derived:

1. Reducing the particle size of fine aggregates and lengthening the curing time increased compressive strength. Using fine aggregates smaller than 0.6 mm resulted in compressive strengths of 76% and 52.35% greater than those cast with fine aggregates smaller than 4.75 mm and 2.36 mm, respectively.
2. Partial replacement of OPC with POCP had a significant impact on the compressive strength of LFC. While a small improvement in strength was observed when replacing 20% of OPC mass with POCP, a significant reduction in strength was recorded at all ages when 30% of OPC was replaced with POCP, with reductions of almost 10%, 25%, 19.5%, and 20% at 7, 28, 75, and 90 days, respectively.
3. Thermal activation of POCP could enhance the compressive strength of LFC when it was partially substituted for OPC. The optimal TPOCP replacement ratio was determined to be 20%.
4. An entire replacement of sand aggregate with fine POC could improve the compressive strength of LFC by almost 54%. As a result, replacing 100% of the MS volume with POC was recommended.
5. When exposed to elevated temperatures, replacing sand aggregate with POC in LFC increased weight loss. However, using POCP and TPOCP had a negligible influence on weight loss.
6. The compressive strength of LFC specimens exposed to 400 °C increased, but those exposed to tempera-

tures above 400 °C experienced a rapid reduction in compressive strength. The rate of strength loss decreased with increasing POC concentrations. The FC-T20-100-1300 specimen had the least strength degradation at 800 °C and exhibited a 10.88% strength reduction.

7. Replacing POC with MS improved LFC's tensile and flexural strengths. The optimal tensile and flexural strengths were reached by replacing POCP or TPOCP for 20% of the cement. At the same replacement ratio, TPOCP specimens had marginally higher tensile and flexural strengths than POCP specimens.
8. Replacing MS with POC fine aggregates improved the MOE of LFC. The maximum increase in MOE was 45.54% when 100% of MS was replaced with POC. Additionally, the MOE values of specimens containing POC,POCP, or TPOCP replacements were higher than the control specimen.
9. Replacing fine aggregates with POC decreased the chemical resistance of the concrete due to increased permeable voids. However, replacing OPC with POCP or TPOCP improved the chemical resistivity of LFC.

LWFC may be effectively confined using steel tubes to enhance its strength. While the technique of confining conventional concrete has been extensively studied (Ayough et al., 2020, 2021, 2022, 2023a, 2023b; Elchalakani et al., 2022), the advantages and potential benefits of utilizing LWFC in this context have been overlooked. It is recommended to conduct further research to thoroughly investigate the performance of LWFC-filled steel tube members. Exploring the behavior and potential advantages of this composite material system can lead to valuable insights and novel applications in the fields of civil engineering and construction.

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