Case Studies in Construction Materials 12 (2020) e00318

Contents lists available at ScienceDirect

Case Studies in Construction Materials

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

Case study

Effect of high-volume ultrafine palm oil fuel ash on the engineering and transport properties of concrete

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ARTICLE INFO

Article history:
Received 14 August 2019
Received in revised form 20 November 2019
Accepted 21 November 2019

Keywords:
By-product
Palm oil fuel ash
Environment pollution
Ultrafine POFA
Green concrete

ABSTRACT

Palm oil fuel ash (POFA) is a by-product in palm oil manufacturing and is currently disposed to open areas and landfills without any previous treatment, thereby causing environment pollution. The use of small-particle-sized ground POFA to prepare ultrafine POFA (UPOFA) is a suitable method to improve its characteristics as a supplementary cementitious material. Although high-volume POFA exhibits reduced mechanical properties in the early ages, heat treatment and further grinding reduce its carbon content and increase its pozzolanic activity. In this study, UPOFA was used to minimise the cement content in concrete mix. Cement was replaced with UPOFA at 0 %, 20 %, 40 %, 60 % and 80 % ratios to produce green concrete. Results revealed that the UPOFA showed remarkable improvement in concrete strength, especially with 20 % and 40 % substitution levels. By contrast, the compressive strength reduced at high replacement levels to be 34.5 MPa at 28 days. The water absorption of concrete containing UPOFA is considerably reduced, thus improving the concrete's durability.

1. Introduction

The world has witnessed a major development in the construction industry, which required and will require substantial construction materials in the past and coming years. Concrete is the most suitable and common among construction materials [1,2]. Cement is the main material in making concrete, because it forms the best bond among other materials [3,4]. However, the utilisation of ordinary Portland cement (OPC) as a binder in concrete manufacturing is discouraged for two reasons, namely, its durability in aggressive environments and the environmental effects associated with the generation of harmful gases, such as CO_2 [5–7]. A 2017 report indicated that the total CO_2 emission from cement production is 2.3 billion tons annually, which produces approximately 7 % of the emitted CO_2 to the atmosphere [8]. The cement consumption was 3270 million metric tons in 2010 and is predicted to increase to 4830 million metric tons by 2030 [9]; thus, environmental pollution has increased gradually. Partial replacement of cement with pozzolanic materials in concrete greatly reduces CO_2 emissions [10,11]. The utilisation of supplementary cementitious materials (SCMs) to produce concrete is also considered a suitable choice to minimise cement, energy consumption and CO_2 emissions [12–14].

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https://doi.org/10.1016/j.cscm.2019.e00318

Although several alternatives of SCMs, such as fly ash (FA), produce satisfying results in concrete properties [15,16], the replacement levels and mechanical properties remain lower than the targeted levels to reduce the CO_2 emissions in the atmosphere. Therefore, various SCMs have been introduced into concrete mixture to enhance its properties and reduce energy consumption. Among these materials is palm oil fuel ash (POFA), which is a by-product material in palm oil manufacturing [17–21]. POFA remains inactive as SCM due to its high carbon content, high value of loss on ignition (LOI) and large particle size. Ultrafine POFA (UPOFA) particles are exposed to extensive grinding to make them smaller and have better properties than normal POFA [22] and to give them high compressive strength [23] for use in self-compacting concrete (SCC) [24] and high-strength concrete (HSC) [20]. However, problems regarding the high replacement level of POFA in concrete mixture include reducing the compressive strength and workability [25,26]. Thus, POFA must be improved through different methods, such as increasing the grinding to generate small particles and performing heating to reduce carbon content [27,28]. Treated POFA (TPOFA) has better performance in concrete than ground POFA (GPOFA) because of the reduced LOI and improved chemical composition [29]. Otaman et al. [30] used UPOFA as cement replacement in various particle sizes to investigate the compressive strength of cement mortar. The use of UPOFA with a fine particle size results in increased compressive strength of alkaline-activated mortar. In 2019, Hamada et al. [26] reported that adding up to 30 % of UPOFA in palm oil clinker concrete enhances the compressive strength and workability of concrete. In 2018, Wi et al. [31] used UPOFA with a particle size ranging between 100 and 150 nm to replace cement. TEM and X-ray diffraction (XRD) results indicated that POFA with nanoparticle size had a high pozzolanic reaction and did not affect the compressive strength at the early age due to absorbed free water for cement hydration. The compressive strength increased with time due to the formation of calcium–silicate–hydrate (C–S–H) gels.

Alsubari et al. [32] concluded that the reduction value of compressive strength at the early curing age became evident with the increasing replacement level of cement with TPOFA. Nevertheless, good compressive strength could be attained for concrete containing TPOFA with increased curing time. Zeyad et al. [20] reported that more than 90 MPa could be achieved for concrete containing high-volume UPOFA at a long curing age. Most previous studies reported that incorporating POFA with a small particle size in concrete can achieve high strength at a later age. Mijarsh et al. [19] used a statistical model to study the effect of TPOFA on cement mortar properties and indicated that the optimum compressive strength of geopolymer mortar at 65 % replacement level was 47.27 ± 5.0 MPa at 7 days. Hussin et al. [33] used UPOFA to replace cement up to 80 % and found that the compressive strength improved with curing age, reaching up to 45 MPa at 360 days. Another study concluded that high-volume TPOFA as cement replacement substantially reduced the compressive strength of SCC at an early age [5]. The above research indicates that the compressive strength of concrete mixtures containing UPOFA is reduced at an early age and then increases gradually at a later age.

The utilisation of normal POFA as cement replacement in concrete production results in the loss of compressive strength, especially at the early age of curing days because of the low pozzolanic in their particles. Many methods, such as adding nanosilica to cement mortar and concrete mix [34,35] and increasing the flexural and splitting tensile strength of POFA concrete by adding waste fibre [36], have been developed to overcome the deficiencies caused by POFA replacement and achieve desirable strength. High-volume UPOFA has been used as cement replacement to study the microstructural properties and hydration temperature of cement mortar [37]. However, few studies have been conducted to show the effect of high-volume UPOFA on concrete properties at the early age. In this study, high-volume UPOFA was used to study its effect on the properties of concrete in various proportions during the early curing age.

2. Experimental details

2.1. Materials

2.1.1. OPC

OPC with specific gravity of 3.15, Blaine's surface area of 329 m^2/kg, 28-day compressive strength of 41.4 MPa and initial and final setting times of 59 and 137 min, respectively, was used.

2.1.2. POFA

Raw POFA was obtained from burnt palm oil biomass, such as fibres and kernel shells, at high temperatures up to 1000 °C to generate electric power in palm oil mills [20]. Raw POFA was collected in adequate quantities from a palm oil factory located in Gambang, Pahang, Malaysia. POFA was treated as performed by previous studies, as shown in Fig. 1 [25]. The same method was utilised before by Islam et al. [38] but without repeating the grinding process for the second time [39]. Many factors, such as the size and number of steel balls, grinding time, milling speed, POFA mass and the thickness of POFA layer, affect the fineness of UPOFA and heating duration [39]. The fine particle size of POFA was examined at the Center of Excellence for Advanced Research in Fluid Flow Lab in UMP, Malaysia, to obtain 0.982 μm, and the product was called UPOFA. Fig. 2 show the particle size distributions of UPOFA. However, preparation of UPOFA to get ultrafine particle size is costly. Therefore, in concrete mix, low volume UPOFA was used.

2.1.3. Aggregates

Normal sand was utilised as fine aggregate with water absorption of 0.67 %, specific gravity of 2.7, particle size between 300 μm and 4.75 mm and fineness modulus of 3.1. The crushing stone was used as coarse aggregate with specific gravity of 2.68, particle size between 4.75 and 10 mm, water absorption of 0.55 % and fineness modulus of 6.7.

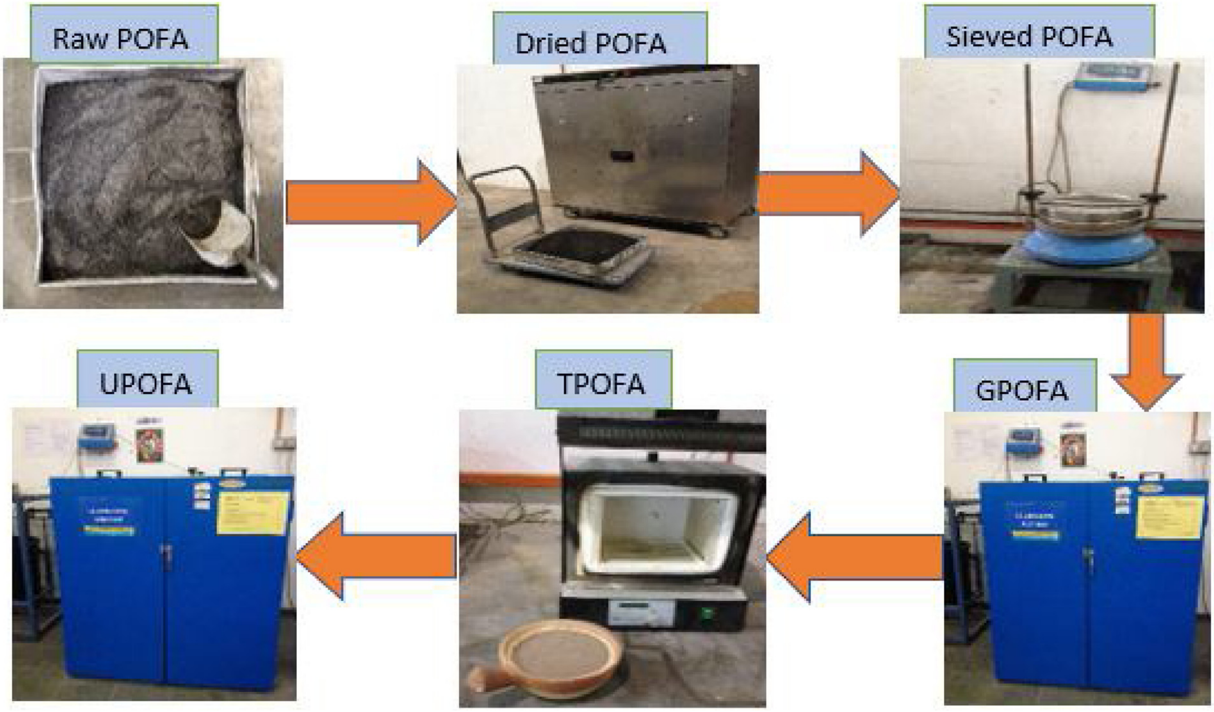


Fig. 1. Preparation of UPOFA.

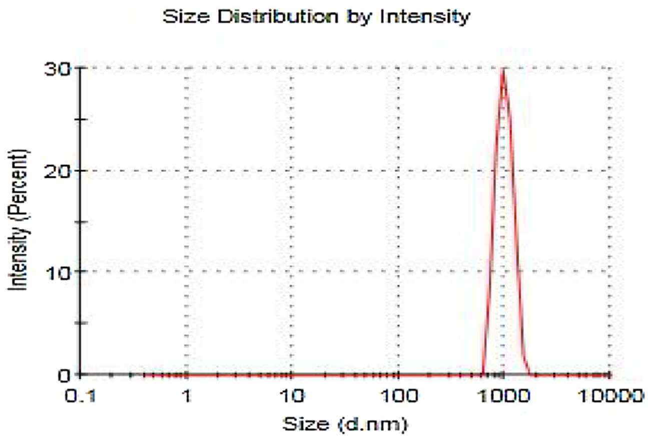


Fig. 2. Particle size distribution of UPOFA.

2.1.4. Water and superplasticiser (SP)

The water supplied to the concrete lab was used to prepare the concrete mixtures. Sika SP was used to improve concrete workability. The SP content was 1 % of binder content for all concrete mixtures.

2.2. Mix design

The total content of cement replacement by UPOFA in this study is shown in Table 1. The water/binder ratio and total binder content were 0.34 and 400 kg/m^3, respectively. All material contents were selected based on trials and previous studies, and the replacement level was determined by weight for the concrete mixtures. In the first stage, the solid materials (coarse and fine aggregates) were mixed for 3 min. Approximately 50 % of mixing water was added to the mix and mixed for 2 min, and the binder materials (UPOFA and OPC) were added gradually to the mix and mixed for 3 min. The other half of the remaining water and SP was mixed carefully, added to the concrete mixture and mixed for 5 min. The produced concrete was cast in cubes and vibrated by a table vibrator. The cube specimens were left for 24 h, removed and soaked in a water tank until

Table 1
Quantities of materials used in the concrete mixtures in kg/m^3.

Mix No	OPC	Water	SP	Fine aggregate	Coarse aggregate	UPOFA
Control mix	400	136	4	760	910	0
N20	320	136	4	760	910	80
N40	240	136	4	760	910	160
N60	160	136	4	760	910	240
N80	80	136	4	760	910	320

the curing age. The purpose of the concrete cubes was to test the compressive strength, ultrasonic pulse velocity (UPV) and water absorption.

2.3. Characterisation techniques for chemical compositions and physical properties

The specific surface area of cement and UPOFA was determined using the Brunauer–Emmett–Teller method with nitrogen gas absorption, as previously conducted [40]. The specific gravity of fine particles was measured by the helium pycnometer method [20,40]. X-ray fluorescence was utilised to identify the elemental compositions of the POFA and OPC by using the nondestructive process, which can be applied to a broad range of materials [17,40].

2.4. Properties of concrete containing UPOFA

Compressive strength test was conducted by collecting three cubic specimens with dimensions of 100 mm at various ages of 7, 14 and 28 days. A compression machine with 3000 K N automatic concrete was used to test the compressive strength with a loading rate of 1 K N/s based on the BS EN 12390-3 [41]. The UPV test of the cube specimens was conducted in accordance with IS: 13311 (Part-1)-1992 [42]. The water absorption test was performed in accordance with the specification of ASTM C 642-13 [43]. The drying shrinkage test was conducted on the basis of ASTM C157 [44] by the prism specimen with dimensions of $100 \times 100 \times 500$ mm^3 in different curing ages. The change in the specimen length was measured from 3 days to 28 days continuously to calculate the drying shrinkage of concrete [45]. After 24 h of casting, the specimens were removed, kept in a water tank for complete curing, removed from the water and left to dry in a laboratory at a temperature of 27 ± 4 °C and relative humidity of 76 % $\pm$ 3 %. All tests were completed by taking the average of three specimens for each testing.

3. Results and discussion

3.1. Chemical composition and physical properties

The chemical composition and physical properties of OPC and UPOFA are shown in Tables 2 and 3, respectively. The POFA particles passed through many treatment steps to acquire a small particle size of 0.982 μm. Therefore, UPOFA was more effective than GPOFA due to its small particle size, which is approximately three times lower in median than that of GPOFA. The UPOFA produced consequently had a higher surface area than OPC and GPOFA. The high content of SiO_2 in the UPOFA could improve the cement hydration to form additional hydration gel (C–S–H) that is required in concrete production.

3.2. Microstructural properties of concrete

3.2.1. Scanning electron microscopy (SEM)/energy-dispersive X-ray spectroscopy (EDX) test of UPOFA

SEM/EDX is an important test to determine the final shape and morphology of UPOFA. The results of the SEM/EDX test indicated that the particles had a porous texture, and the shape ranged between semicircular and angular. The particle size was smaller than that of GPOFA particles. The EDX test was conducted to determine the quantitative composition of materials.

The physical properties changed in the UPOFA because of the treatment. The specific surface area of UPOFA was 1.962 m^2/g, and the particle size was 982 μm. The micrograph of SEM/EDX illustrates that the carbon content was reduced due to the

Table 2
Chemical composition of UPOFA and OPC.

Binder type	Chemical composition of binder											
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	Na_2O	K_2O	SO_3	MnO	P_2O_5	LOI
OPC	26.1	8.54	4.69	54.8	0.358	0.427	0.186	0.97	2.77	0.137	0.177	0.53
UPOFA	67.5	4. 2	8.12	3.97	2.72	0.229	0.115	8.45	0.535	0.07	2.47	1.48

Table 3
Physical properties of binder materials.

Materials	Specific gravity kg/m^3	Specific surface area (m^2/g)	Median particle size, d50 (μ m)
OPC	3.15	0.785	6.85
UPOFA	2.52	1.962	0.982

exposure of UPOFA to heat treatment. The SiO_2 in UPOFA increased more than that in GPOFA due to the reduced LOI value and carbon content and the increased Fe_2O_3 and Al_2O_3 contents. Consequently, the UPOFA could be classified as a mineral admixture within class F in accordance with ASTM C618 [46]. The SEM/EDX test also illustrated that the colour changed from black to reddish grey. The results of the EDX test showed that the chemical compositions of UPOFA had different concentrations compared with those of GPOFA. SiO_2, Al_2O_3 and Fe_2O_3 exhibited the highest concentrations among the oxides. Fig. 3 shows the SEM/EDX results of UPOFA.

The colour of POFA changed due to the various heat treatments. The production of carbon in GPOFA resulted in the black colour and was the main cause of the reduced efficiency of POFA. The SEM result showed a decreased carbon content, as depicted in Fig. 3. Zeyad et al. [20] reported that the fine particle size, low carbon content, reduced LOI, high surface area and high amorphous content led to the superior pozzolanic properties of UPOFA and thus exhibited important effects on the transport and engineering properties of HSC.

3.2.2. XRD analysis of UPOFA

The XRD pattern phases found in UPOFA are relatively similar to those from earlier studies [25,47,48]. UPOFA contains SiO_2 as quartz or cristobalite and $K_3Al_2(PO_4)_3$. The various components in the UPOFA particles play an important role in

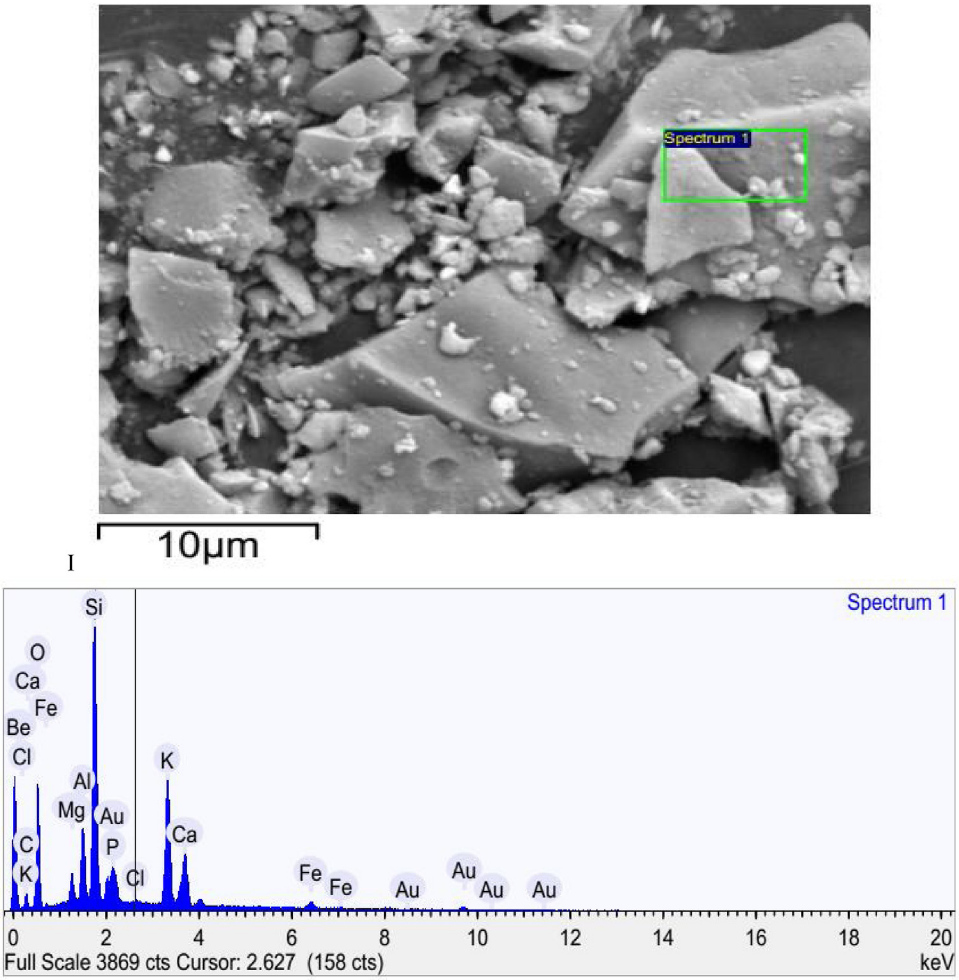


Fig. 3. SEM/EDX test of UPOFA.

enhancing the reactions required between UPOFA and additives. The XRD result of UPOFA showed the peaks of SiO_2 at 2θ angles in the positions of 20.4°, 26.2°, 36.22°, 39.1°, 50.14°, 55.8°, 66.1° and 75.4°. The highest peak was approximately 26.7°. The concentrations of the SiO_2 peaks differed depending on the position on 2θ angles, as depicted in Fig. 4. The XRD pattern of this study is similar somehow to that of POFA used and investigated by previous studies [25,49]. The largest surface area of the UPOFA was 1.962 m^2/g, thereby enhancing the reactivity and the reaction rate, as reported by previous studies [30]. Therefore, the heating treatment and grinding process have a great influence on the physical properties of the UPOFA in terms of specific gravity, particle size and specific surface area.

Pozzolanic activity in POFA particles has an effective role in improving the concrete properties and thus produces concrete with low cost and minimum CO_2 emission. Pozzolans are siliceous or siliceous and aluminous materials that react with portlandite because of cement hydration, thereby generating secondary compounds that enhance strength properties (ASTM 2000).

Zeyad et al. [20] showed the effect of pozzolanic reactivity in POFA on HSC. They found that the high surface area, small particle size and glassy phase (70.59 %) of POFA make it a good pozzolanic material to enhance concrete strength. The low pozzolanic reactivity of POFA caused delays in strength development at the early age [50]. The high pozzolanic activity of POFA enhanced the microstructure, mechanical properties and durability performance of cement concrete when used as a SCM, especially at later ages [51,52]. Sam et al. [9] examined the pozzolanic activity of POFA by Chappelle's test and found a value of 670 mg/g, which was three times lower than that of metakaolin. The treatment methods that incorporated heat treatment and ball milling changed the properties of POFA. The quartize phase (SiO_2), as shown in Fig. 4, was the main crystalline phase.

3.3. Workability of concrete

The workability determined by the slump test in accordance with BS EN 12350-2 [53] is shown in Fig. 5. Incorporation of UPOFA as cement material in concrete enhanced the concrete workability. The clear increase in the concrete workability was due to the various binders of the concrete, such as POFA and OPC; the specific gravity of UPOFA is also lower than that of OPC. The excess paste volume in comparison with OPC could have functioned better in coating the aggregate particles, filling the gaps among the aggregate particles and providing lubrication for aggregate particles to move during the slump test, hence increasing the workability. This increase occurred despite the fact that the UPOFA has smaller particle size and greater surface area than OPC and the constant water/binder ratio and SP dosage used in all concrete mixes. Thus, a low dosage of SP could lead to constant workability. The high workability of UPOFA concrete was reported by previous studies with increased SP dosage to maintain constant slump for all concrete mixtures [23,54,55]. Likewise, another study used UPOFA as cement replacement with increased SP in cement mortar to achieve a consistent flow [56]. Previous studies observed that the high content of LOI in POFA particles minimised the mechanical properties of concrete, especially the workability and compressive strength, due to the high carbon content of untreated POFA [23,54–56]. The high carbon content of POFA particles reduced the SP efficiency [39].

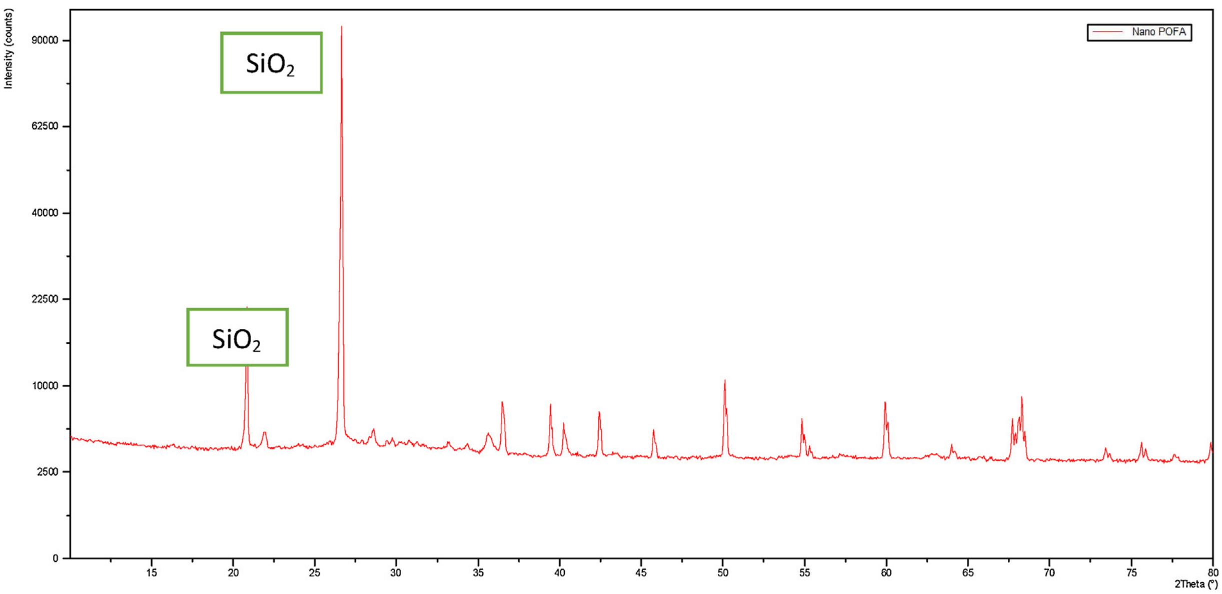


Fig. 4. XRD test of UPOFA.

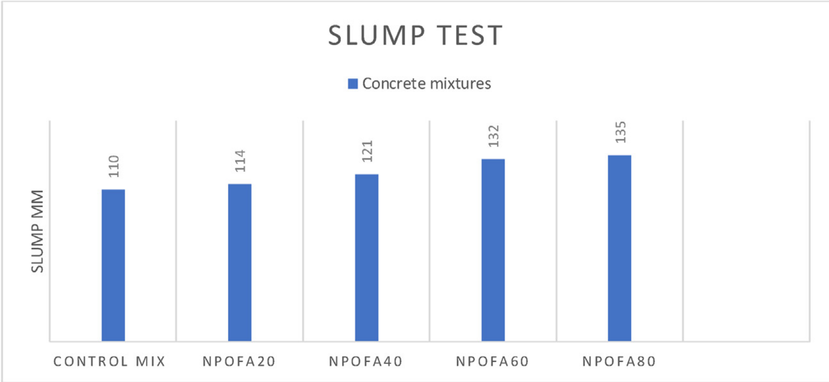


Fig. 5. Slump test of concrete containing UPOFA in various percentages.

The results of this study implied that increased UPOFA replacement with low LOI increased the workability. This study is in line with Johari et al. [25], who stated that the integration of UPOFA leads to increased workability with a constant water/binder ratio.

3.4. Mechanical properties of concrete

3.4.1. Compressive strength

Fig. 6 illustrates that the inclusion of UPOFA in concrete mix led to improved compressive strength at a later age due to the high pozzolanic reaction of UPOFA compared with that of only OPC [57]. The high content of SiO_2 in UPOFA increased the pozzolanic reaction and thus improved the mechanical properties in concrete mixtures [58–60]. The 7-day compressive strengths of UPOFA20, UPOFA40, UPOFA60 and POFAN80 were less than those of the control mix by approximately 6.7 %, 19.8 %, 38 % and 52.1 %, respectively. The 14-day compressive strengths for the control mix, UPOFA20, UPOFA40, UPOFA60 and UPOFA80 mixtures were 41.5, 40.1, 36.8, 30.2 and 26 MPa, respectively. The 28-day compressive strength improved especially for the concrete mixtures containing UPOFA to 109 %, 102 %, 80 % and 72 %, as presented in Fig. 6. Hence, all UPOFA concrete mixes improved at 28 days compared with those at 7 days.

The improvement in the compressive strength of the concrete comprising UPOFA with increasing time was due to the pozzolanic reaction between UPOFA and Ca(OH)2. The same result was obtained by Tangchirapat et al. [54], who used POFA as cement replacement at three levels of 10 %, 20 % and 30 % and yielded compressive strengths of 58.5, 59.5, 60.9 and 58.8 MPa. Johari et al. [25] used high-volume POFA to replace cement in HSC. They concluded that the compressive strength of concrete comprising POFA at 3 and 7 days was lower than that of the normal concrete, particularly with high POFA contents. However, the compressive strength was higher at 28 days, and POFA40 gave the highest compressive strength of

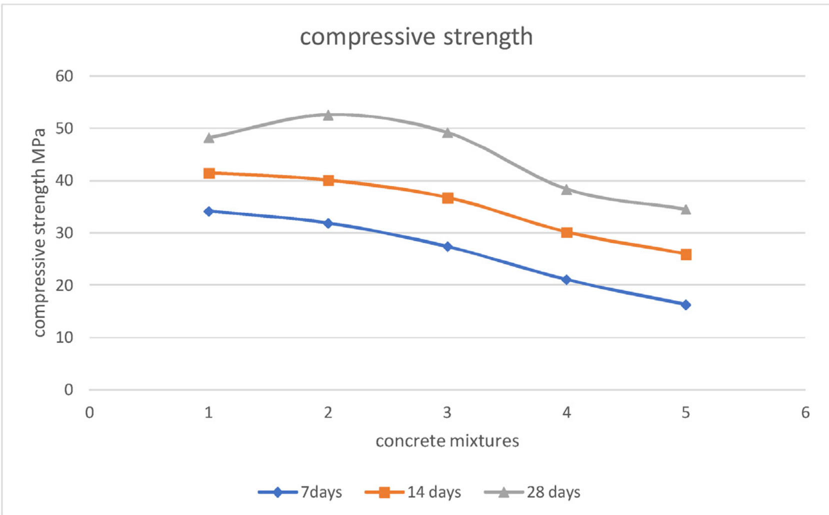


Fig. 6. Compressive strength of concrete comprising UPOFA at various ages.

104 MPa, this trend was attributed to an increasing in the pozzolanic activity due to the high specific surface area and small diameter of UPOFA.

Zeyad et al. [40] reported that an increase in cement replacement by UPOFA resulted in decreased compressive strength, especially at the early curing age. The 28-day strength was improved to reach 105.5 MPa at the 40 % replacement level at 180 days. A low compressive strength at the early age was obtained, because the pozzolanic material of UPOFA can be highly active at a later age, as mentioned by previous studies [20,25,37]. POFA is considered a pozzolanic material; therefore, the strength development of the resulting concrete is based on the reaction of calcium hydroxide (CH) with SiO_2 from POFA to form C–S–H gels. In the high-replacement cement by POFA, the reduction in the pozzolanic reaction might be due to the reduction in CH formed from cement hydration. Consequently, the compressive strengths of POFA mixtures were less than that of the concrete with low POFA percentage.

3.4.2. Ultrasonic pulse velocity (UPV)

UPV is a nondestructive test to determine concrete quality [61]. The UPV test of UPOFA concrete was conducted to analyse the uniformity of concrete, cracks, defects and cavities [62,63]. Regardless of the material quality and type, the pulse velocity in a material depends on its elastic and density properties, which influence the concrete strength. The UPV test is an indicator of the type and strength of the aggregates used [64]. A low UPV indicates the presence of voids in the concrete composite. The 7-day UPV for all concrete mixtures ranged between 3058 and 3315 km/s, and the 28-day UPV values for all mixes ranged between 3323 and 3541 km/s, as shown in Fig. 7. The quality of the concrete mixtures was good, as classified by another study [65].

Fig. 7 shows that the maximum UPV at the replacement level of 40 % of UPOFA with cement was 3541 km/s at 28 days. The high UPV might be due to the high pozzolanic reaction of UPOFA, which acquired the high density and compressive strength of the concrete material. The result of this study is somewhat similar to that obtained by Islam et al. [38].

3.5. Durability properties of concrete

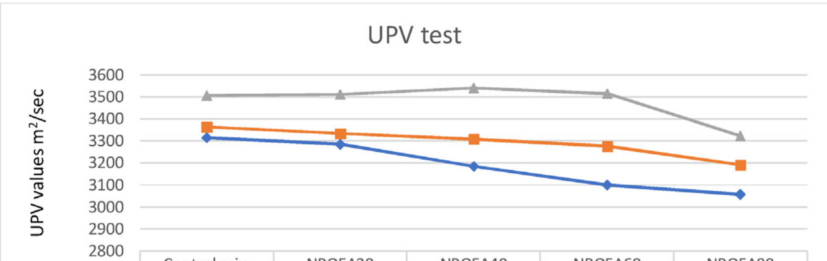
3.5.1. Water absorption

The water absorption value is important to determine concrete's ability to resist external environmental conditions [66]. Fig. 8 shows the water absorption for five different mixtures with various proportions of UPOFA, including the control specimen. Water absorption test of all concrete mixtures was performed on the 100 mm^3 cube specimens at ages of 7, 14 and 28 days. The specimens were dried in an electric oven for 2 days before the test. Then, water absorption of the concrete samples was identified after immersion in water for 30 min. The water absorption value can be obtained from the equation below:

$$\text{Water absorption \%} = \frac{Ws - Wd}{Wd} * 100\%, \tag{1}$$

where Ws is the mass of specimen on a dry surface saturated, and Wd is the mass of the specimen in air.

The results of water absorption of specimens cured for 7 days were 3.6 %, 3.2 %, 3.1 %, 3.0 %, 2.8 % and 2.7 % for the control mix, UPOFA20, UPOFA40, UPOFA60 and UPOFA80, respectively. The water absorption values decreased to 3.2 %, 2.9 %, 2.9 %, 2.6 % and 2.4 % at 14 days and subsequently to 3.0 %, 2.7 %, 2.5 %, 2.4 % and 2.2 % at 28 days of curing. The water absorption of the control mix, UPOFA20, UPOFA40, UPOFA60 and UPOFA80 was reduced by 16 %, 15 %, 19 %, 20 % and 21 %, respectively. The results proved that the high content of UPOFA in concrete mix led to the reduced porosity compared with other mixtures.



	Control mix	NPOFA20	NPOFA40	NPOFA60	NPOFA80
7 days	3315	3286	3186	3101	3058
14 days	3365	3334	3308	3276	3191
28 days	3507	3512	3541	3515	3323

Fig. 7. UPV test of concrete containing UPOFA.

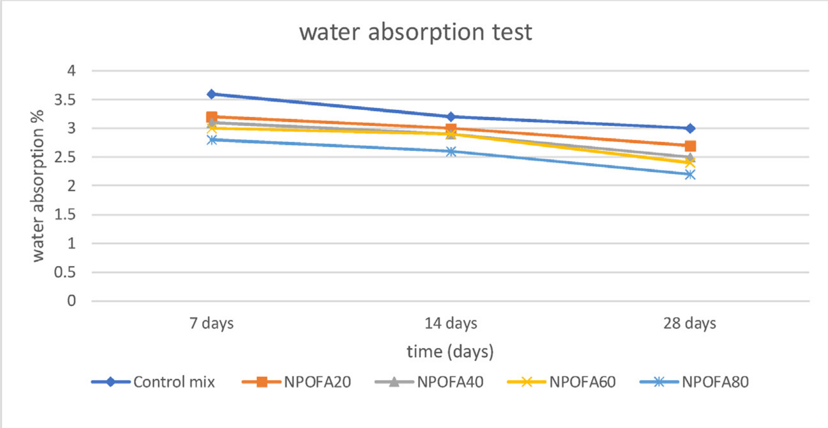


Fig. 8. Water absorption of concrete containing UPOFA.

Increasing the replacement level of UPOFA in concrete mixtures reduced the water absorption, especially at 28 days of curing. The low water absorption may protect the concrete from the acid and sulphate attack, thus enhancing the concrete's durability [20].

3.6. Time-dependent properties of concrete

3.6.1. Dry shrinkage

Drying shrinkage is a crucial property of concrete. It occurs usually when specimens are exposed to humidity and ambient temperature and is related to moisture loss [67]. It is a time-dependent process and may require a long time to complete [8]. Drying shrinkage also results in reduced stress in prestressed members [68]. It should be tested in case of lightweight aggregate concrete [69,70]. Many factors affect shrinkage, such as cement content and type, w/c, aggregate quantity and elastic modulus, hydration degree and admixture amount and characteristics [71,72]. For all concrete mixtures, the drying shrinkage value increased with age, as observed in Fig. 9. The highest drying shrinkage values for all ages were obtained for the control specimen, whereas the lowest values were recorded with the UPOFA80 mix.

As shown in Fig. 9, the shrinkage rate increased with time. At 3 days, the drying shrinkage of UPOFA80 was 404 microstrains and gradually increased to 830 microstrains at 28 days. UPOFA80 had the highest replacement level of POFA; therefore, its drying shrinkage had the lowest value, as proved by [34,73]. The highest values of drying shrinkage ranging from 850 microstrains to 1393 microstrains for concrete ages of 3 and 28 days, respectively, were generated for the control specimen.

The drying shrinkage values of the concrete mixtures (UPOFA20, UPOFA40, UPOFA60 and UPOFA80) in 28 days reduced by 10 %, 17 %, 27 % and 40 %, respectively, compared with that of the control specimen. The decreases in the drying shrinkage value of concrete, including UPOFA, at various percentages could be attributed to the high packing effect and pozzolanic

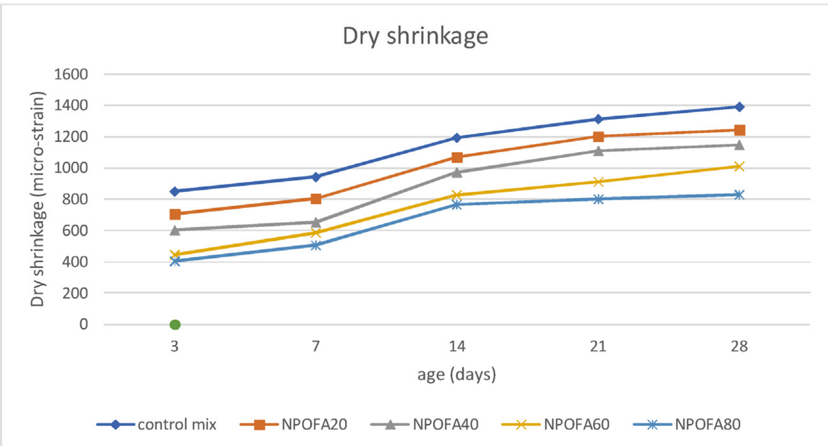


Fig. 9. Drying shrinkage test.

activity. The nanoparticle size of UPOFA improved pozzolanic reactions, which caused pore modification, reduced water loss and thus decreased drying shrinkage [5].

Tangchirapat et al. [54] stated that the HSC containing GPOFA had lower drying shrinkage than control specimen for any POFA replacement level. In HSC, the densification of the pore structure of POFA caused a lower drying shrinkage value. The incorporation of UPOFA resulted in decreased pore sizes in concrete and transformed large pores into fine pores that led to reduced water evaporation and drying shrinkage value. Concrete containing SCMs, such as POFA and FA, has a positive effect on reducing water evaporation and drying shrinkage [74]. Therefore, the utilisation of high-volume UPOFA in concrete can reduce drying shrinkage and thus improve the concrete's durability with time.

4. Conclusion

This study evaluated the properties of concrete containing UPOFA, and the following conclusions were obtained:

1 UPOFA had a large surface area, a small particle size and a low LOI value due to decreased carbon content to achieve SCM with high pozzolanic reaction.
2 The SEM/EDX result of UPOFA showed that its particle size is smaller than that of cement and that it has a porous texture and semicircular and angular shapes. The main component is SiO_2.
3 UPOFA reduced the concrete density due to the light weight and specific gravity of UPOFA, which were lower than those of OPC and GPOFA.
4 UPOFA exhibited low compressive strength at the early age, especially at 7 days. The strength gradually increased at 28 days, especially at replacement levels of 20 % and 40 % of cement with UPOFA contents.
5 The concrete containing UPOFA recorded low water absorption, especially at high UPOFA contents. Therefore, this concrete may have high resistance to environmental attacks, such as sulphate and acid attacks.
6 The drying shrinkage of concrete increased with time but decreased with added UPOFA as cement replacement, thus being an advantage in concrete production

In summary, UPOFA has substantial effects on concrete properties, especially in the later age. Thus, these materials can be used to enhance the sustainability of concrete materials by using renewable and by-product materials.

Declaration of Competing Interest

There is no conflict.

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