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MECHANICAL PROPERTIES AND THERMAL BEHAVIOUR OF TWO-STAGE CONCRETE CONTAINING PALM OIL FUEL ASH

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ABSTRACT: Two-stage concrete (TSC) is a special type of concrete which is made by placing coarse aggregate in a formwork and injecting a grout either by pump or under the gravity force to fill the voids. Over the decades, the application of supplementary cementing materials in conventional concrete has become widespread, and this trend is expected to continue in TSC as well. Palm oil fuel ash (POFA) is one of the ashes which has been recognized as a good pozzolanic material. This paper presents the experimental results on the performance behaviour of POFA in developing physical and mechanical properties of two-stage concrete. Four concrete mixes namely, TSC with 100% OPC as a control, and TSC with 10, 20 and 30% POFA were cast, and the temperature growth due to heat of hydration and heat transfer in the mixes was recorded. It has been found that POFA significantly reduced the temperature rise in two-stage aggregate concrete and delayed the transfer of heat to the mass of concrete. The compressive and tensile strengths, however, increased with the replacement of up to 20% POFA. The results obtained and the observation made in this study suggest that the substitution of OPC by POFA is beneficial, particularly for prepacked mass concrete where thermal cracking due to extreme heat rise is of great importance.

Keywords: Two-stage concrete; Palm oil fuel ash; Heat of hydration; Heat transfer; Mechanical properties.

1. INTRODUCTION

Two-stage concrete (TSC) or prepacked concrete drives its name from the unique placement method by which it is made. Unlike traditional concrete, it is made in two stages. In the first stage the coarse aggregates are filled in the form work, and a cement based grout is injected or pumped into the aggregate mass in the second stage [1–5]. In the gravity method, the grout penetrates through the aggregates from the top surface to the bottom of the formwork under its own weight and mostly useful for grouting concrete sections with a depth up to 300 mm [6]. In the pumping method, the mixed grout is pumped from the bottom of the mould into the aggregates through a pipe [7, 8]. The prepacked aggregate concrete has proved particularly useful for plain or reinforced concrete in a number of applications like underwater construction, concrete and masonry repair, works where placement of concrete by normal traditional methods is difficult, large mass concrete where low cement content and low heat of hydration are required [1, 6].

During the process of hydration, the compounds of cement react with water to acquire stable low-energy state, and the process is accomplished by the release of energy in the form of heat. The quantity of heat evolved upon complete hydration of a certain amount of un-hydrated cement at a given temperature is defined as heat of hydration [9, 10]. The temperature of concrete mix due to hydration process is mainly controlled by materials, mix properties and by environmental factors. The heat of hydration is also related to the chemical composition of the cement. The major component of Portland cement is calcium; therefore the expansion of total heat will be affected by the amount of calcium in the cement. High cement content may be useful to obtain higher strengths of concrete at early ages, but the larger heat generated due to the chemical reactions causes undesirable durability problems like shrinkage and thermal cracks in the concrete [11, 12].

The utilization of pozzolanic materials in reducing the heat of hydration of concrete is well recognized [12, 13]. The first use of fly ash was made in 1950 at the Otto Holden Dam on the Ottawa River near Mattwa, Ontario [14] and it has been observed that concrete containing 30% fly ash exhibited 30% lower temperature than that of plain concrete. Other types of pozzolanic materials like slag, silica fume and rice husk ash have been revealed to influence the concrete by lowering the heat in massive concrete [15-18].

With the development of concreting techniques and materials, utilization of different pozzolanic materials in concrete construction has also been increased. These pozzolanic materials are used in the concrete industry for their technical, economic and ecological benefits. One of the latest inclusion in the ash family is palm oil fuel ash (POFA), a by-product of thermal power plants in which palm oil kernel shell and husk are burnt in palm oil mills as fuel. Amongst the oil palm growing countries in Southeast Asia, Malaysia is the second largest producer of palm oil and palm oil products in the world. In 2007, approximately 3 million tons of palm oil fuel ash have been generated in Malaysia, and this production rate is expected to rise due to the increased plantation of palm oil trees [19-23].

It is generally known that the conductivity and the heat transfer coefficient have relatively greater influence on the temperature gradient along with the concrete structure. Heat transfer of concrete is greatly affected by mix proportions, type of aggregate and cementitious materials. In contrast to study on thermal properties of normal concrete, works on thermal conductivity and the specific heat of two-stage concrete, however, are not many [24-28].

The replacement of ordinary Portland cement (OPC) by POFA in two-stage concrete is a new area of research, which is gaining significant attention. Although, a number of research works have been carried out on the use of POFA in conventional concrete, there is no literature available concerning the heat transfer properties of two-stage concrete containing POFA. In view of the utilization of POFA as a supplementary cementing material to prepare grout in two-stage concrete, research works have been undertaken in examining various properties of two-stage concrete. This paper presents experimental results on the effect of palm oil fuel ash in reducing the heat of hydration and strength properties of the concrete.

2. MATERIALS AND TEST METHODS

2.1 Collection and preparation of POFA

POFA is a byproduct of thermal power plants in which palm kernel shell and husk are burnt in palm oil mills as fuel. In this study, POFA was obtained from a factory in Johor, southern state of Malaysia. The collection of ash was done at the foot of the flue tower where all the fine ashes are trapped, while escaping from the burning chamber of the boiler. After collection, the raw POFA was dried in an oven at a temperature of 110ºC for 24 h. It was sieved through 300 µm sieve to remove large particles and other impurities thereby reducing the carbon content to prevent glassy phase of crystallization. The ashes were then ground in a modified Los Angeles abrasion test machine having stainless steel bars of 12 mm diameter and 800 mm long.

2.2 Concrete materials and mix proportions

The selection of coarse aggregate is of great importance with respect to the concreting in two-stages since the applied stresses in concrete are transferred first to the coarse aggregate particles and then to the hardened grout [29]. The coarse aggregate used in this study was angular and irregular crushed granite with specific gravity of 2.7, having 0.5% water absorption and the size of 20–38 mm. A saturated surface dry mining sand with a fineness modulus of 2.3, 100% passing through ASTM sieve no. 14 having specific gravity and water absorption of 2.6 and of 0.70% respectively was used as fine aggregate. The cement used in this study was ordinary Portland cement (ASTM Type I). To improve the fluidity, RHEOBUILD 1100 (HG), a polymer based superplasticizer was employed in the grout.

The mix proportions of the grout were prepared at water binding (w/b) ratio of 0.50 and cement to sand (c/s) ratio of 1/1.5. The dose of superplasticizer was 1% by weight of the binder. In this study, the mixture proportions of the grout were determined according to the ASTM C938 [30]. A total of four mixes were made: one with OPC alone as control and the others with OPC replaced by weights of 10, 20 and 30% POFA. The relative mix proportions of TSC mixes are given in Table 1.

Table 1 Mix proportion of TSC samples

Mix	Proportion by weight (kg/m^3)					
	Water	Cement	POFA	SP	Fine aggregate	Coarse aggregate
OPC	189	378	–	3.78	548	1321
10% POFA	189	340	37.8	3.78	548	1321
20% POFA	189	302	75.6	3.78	548	1321
30% POFA	189	265	113.4	3.78	548	1321

2.3 Preparation of test specimens

The casting of prepacked aggregate concrete occurs in two stages, placing the coarse aggregate in the mould and injecting the grout to fill the gaps between the aggregate particles. The cylinder with un-plasticized polyvinyl chloride tubes having 150 mm diameter were placed on a plywood formwork base, the details of which are shown in Fig. 1(a). To ensure uniform rise of grout across the section in the tube, a cone was attached to the platform under each tube. The cone was made from mild steel and contained a steel ball, placed at the bottom of the cone to act as a one way valve. After placing the coarse aggregate in the tube, it was capped with a perforated plywood cap, which allowed the entrapped air to escape from the tube, while also restraining the top portion of the coarse aggregate from the lifting during the grouting process.

In the second stage, the grout was injected into the gaps of the coarse aggregate by pump and gravity methods. The mixing of the grout was prepared by an electric mixer which took about 5 min to get the desired grout of well consistency. When POFA was used in the grout, it was first blended with dry OPC before adding water. In case of superplasticizer, it was added at the time of final mixing of the grout.

After mixing of grout, the whole mass was transferred into the grout hopper and was stirred continuously, while grouting was in progress to avoid any segregation in the grout mixture. The hand pump, connected to the grout hopper, was used to inject the grout through the aggregates into the tubes. As the tube was full, grout pumping was stopped and the time taken to fill the tube was recorded. The average time required to fill the 1000 mm long tube was about 100 s. In the gravity method, grout was injected into the cylindrical mould through a PVC pipe under gravitational force, as shown in Fig. 1(b). After 24 h of casting, the concrete specimens were demoulded and immersed into the water tank until the test. All the tests were performed at an average room temperature of 27ºC with the relative humidity (RH) of 80 ± 5%.

Fig. 1 Methods of grouting in two-stage concrete: (a) pump method and (b) gravity method

2.4 Testing of grout and concrete specimens

The effect of POFA content at different levels of replacement on grout consistency were studied to investigate the flow characteristics of the grout following ASTM C939 [31]. The measurement of bleeding was carried out according to ASTM C940 [32]. Grout with a volume of 800 ± 10 ml, was poured inside a 1000 ml glass graduate for various POFA contents of 0, 10, 20 and 30% mix proportions to measure the bleeding of the grout mixture. Cube specimens with dimensions of 70 x70 x 70 mm were made to determine the 28 days dry density of the different grout mixtures. The compressive and splitting tensile strength tests were conducted with 150 mm x 300 mm cylinder specimens according to ASTM C39 [33] and ASTM C496 [34] respectively.

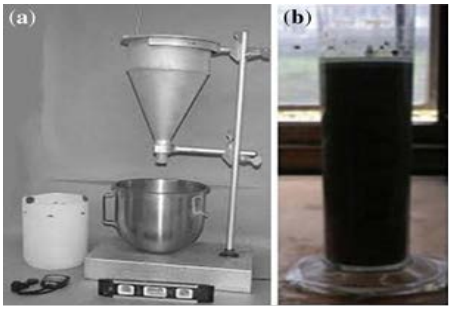

Fig. 2 (a) Measurement of grout fluidity and (b) Test for grout bleeding

2.5 Measurement of heat of hydration

Heat of hydration is the property of cement concrete or mortar in its hardening state. In this study, cubical plywood with sides 280 mm was internally insulated the pack with 76 mm thick expanded polystyrene acting as the insulator. Concrete mix with 100% OPC and those with OPC replaced by 10, 20 and 30% by weight were cast into the cylinder mould of 150 mm diameter 300 mm height. Prior to casting, a thermocouple (Type K) was inserted into the center of each sample and, the cylinder was filled with coarse aggregates and grout injected into the mould through the drilled hole of the polypropylene foam lid, and was connected to a computer driven data acquisition system. The insulated cubical box and the test arrangement are illustrated in Fig. 3. When grout was poured into the mould, heat was liberated by hydration process and subsequently increased the temperature of the two-stage concrete mass. This rise in temperature and succeeding drop was observed with a close interval during the first 24 h and lesser frequency afterwards until the temperature dropped close to the initial reading. The measurement of temperature was continued up to 140 h for all the mixes.

Fig. 3 Test setup for the measurement of heat of hydration

2.6 Measure of heat transfer

Heat transfer test was conducted on cylinder specimen of 150 mm diameter and 300 mm height, which was used for the heat of hydration test at the age of 28 days. To avoid any penetration of water into the concrete, all TSC specimens were covered with a thin plastic sheet. To protect the thermocouple against sudden impacts, a PVC pipe with 2 cm diameter was employed (Fig. 4). All the samples were kept in the water tank at the initial water temperature of about 34ºC. On heating, the temperature of water gradually raised up to 100ºC and the measurement of temperature was continued till the end of test.

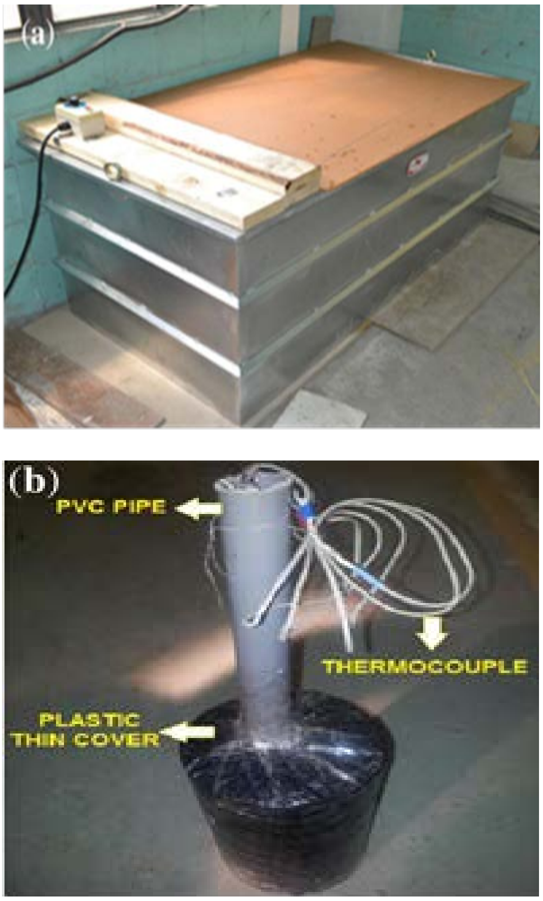

Fig. 4 Heat transfer test arrangements: (a) boiler water tank and (b) concrete sample

3. RESULTS AND DISCUSSION

3.1 Properties of POFA

Palm oil fuel ash is grey in colour that becomes darker with increasing amounts of unburnt carbon content. The particles have extensive range of sizes, but they are relatively spherical (Fig. 5). This spherical shape provides balling effect among the particles that ultimately improves the workability of the cement matrix. The physical properties and chemical composition of OPC and POFA are presented in Table 2. It can be observed that POFA have a higher Blaine fineness and lower specific gravity as compared to OPC. The chemical composition suggests that POFA contains low calcium oxide and may be classified between class F and class C according to the ASTM C618 [35].

It is interesting to note that the present-day classification system for grouping of ashes into class N, class F and class C is not adequate to appraise their total usefulness, particularly for agricultural ashes. Considering the origin and type, this ash is, however, neither of class C nor of class F.

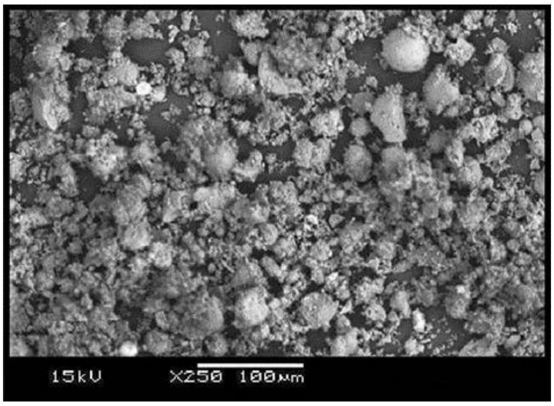

Fig. 5 Scanning electron micrograph of POFA

3.2 Properties of grout

The basic properties of the grout in the manufacture of two-stage concrete are its flow characteristics i.e. grout consistency and bleeding properties. The effect of POFA content on flow, bleeding and density of fresh grout are shown in Fig. 6. Data presented in Table 3 depict that as the POFA content increased, the fluidity of the grout also increased.

At w/b and c/s ratios of 0.5 and 1.15 respectively, grout with 10% replacement showed a flow time of 13.9 s, whereas grout with 30% replacement exhibited a lower value of 12.1 s for the same w/b and c/s ratios as compared to that of 15.3 s for OPC grout. It can be seen in Fig. 6 that the bleeding of grout mixes containing POFA was relatively less than that of OPC grout. The bleeding capacity of grout which is the ratio of the bleed water to mixing water, for OPC grout with a w/b ratio of 0.5, for example, was 10.4%; whereas the bleeding capacities of the grouts containing 10, 20 and 30% POFA for the same w/b ratio were 9.1, 8.6 and 8.0% respectively. This indicates that POFA used in the grout reduced the amount of bleeding significantly.

The dry density of the OPC and POFA grout mixes is illustrated in Fig. 6(c). It was found that the density of the grout mixes containing POFA was lower than that in OPC mix. This is expected due to the lower specific gravity of POFA (2.42) particle compared to OPC (3.15) one. For instance, the lowest density of 2116 kg/m^3 was obtained for the grout containing 30% POFA, which is 1.5% lower than that of 2145 kg/m^3 for grout with OPC only. The observation made in this study corroborates the research findings of Mohammadhosseini et al. [18] and Tangchirapat et al. [36].

Table 2 Physical properties and chemical composition of OPC and POFA

Physical properties				Chemical composition (%)							
Material	Specific gravity	Blaine fineness	Soundness	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	LOI
OPC	3.15	3990	1.0	20.4	5.2	4.19	62.4	1.55	0.005	2.11	2.36
POFA	2.42	4930	2.0	62.6	4.65	8.12	5.7	3.52	9.05	1.16	6.25

Table 3 Properties of grout and strength development of concrete

Mix	Grout fluidity (s)	Bleeding (%)	Density (kg/m^3)	28-day compressive strength (MPa)		28-day tensile strength (MPa)	
				Pump	Gravity	Pump	Gravity
OPC	15.3	10.38	2145	33.0	32.6	2.9	2.8
10% POFA	13.9	9.13	2130	35.1	32.9	3.2	2.9
20% POFA	12.8	8.63	2120	33.8	33.2	2.9	2.8
30% POFA	12.1	8.00	2115	28.7	24.9	2.7	2.6

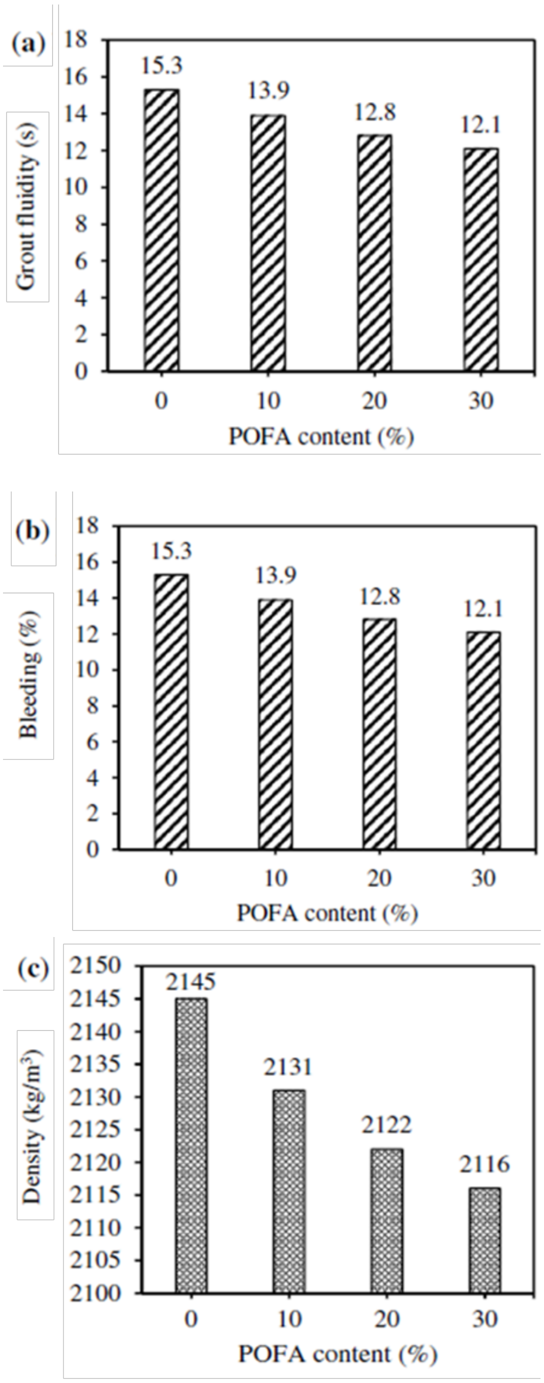

Fig. 6 Properties of fresh grout: (a) fluidity (b) bleeding and (c) density containing various amount of POFA

3.3 Compressive and splitting tensile strength

The investigation of the strength of two-stage concrete for pump and gravity methods was carried out at the age of 28 days. The compressive strength data given in Table 3 reveal that using up to 20% POFA in the grout, the compressive strength of TSC was found to be higher than that of OPC for both pump and gravity samples.

Strength data illustrated in Fig. 7 shows that the highest compressive strength of 35.10 MPa was obtained in the pumped TSC with 10% POFA, while sample with 20% POFA content showed 33.85 and 33.20 MPa compared to that values of 33.00 and 32.60 MPa respectively for pump and gravity filled TSC with OPC only. Further increase in POFA content, however, reduced the strength of concrete made by both pump and gravity methods.

The splitting tensile strength of two-stage concrete made with pump and gravity methods was also investigated at the age of 28 days. The test results presented in table 3 revealed that higher the amount of POFA, lower was the tensile strength value. For example, the highest strength of 3.25 MPa was recorded for 10% POFA mix filled by pump, whereas a value of 2.90 MPa was obtained for TSC containing OPC alone for the same method. A lowest tensile strength of 2.75 MPa was, however, recorded for specimen containing 30% POFA having 0.50 w/b ratio, which is around 5% lower than that of PAC with OPC alone.

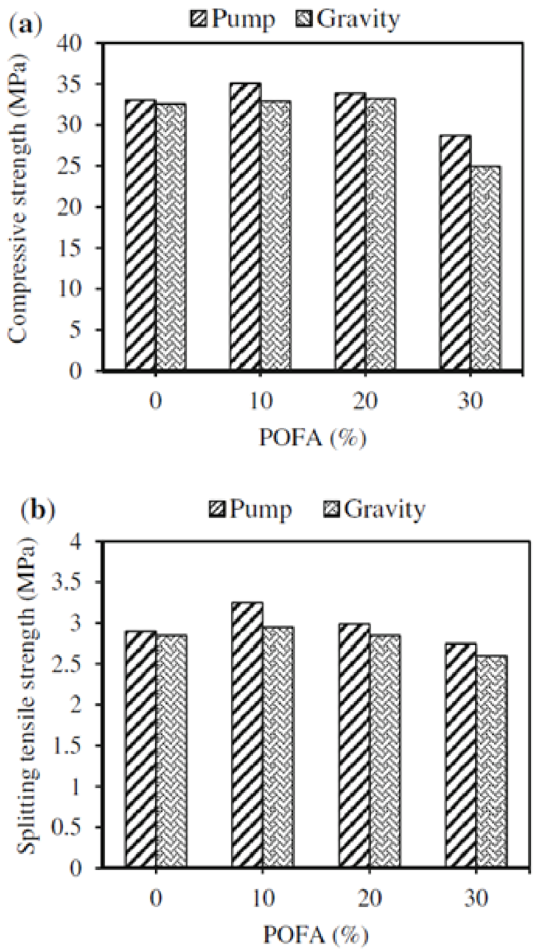

Fig. 7 Effect of POFA on (a) Compressive and (b) splitting tensile strength of TSC at 28 days

3.4 Heat of hydration

The time-temperature histories of two-stage concrete mixes are presented in Table 4 and the progressions of temperature due to heat liberation during the hydration process, obtained at the center of insulated TSC specimens of all the concrete mixes are shown in Fig. 8. It can be seen that initially, the temperature increased almost equally in all the mixes. However, with the increase in time, the effect of the replacement of OPC with POFA can clearly be detected. In two-stage concrete the grout containing POFA reduced the total temperature rise and furthermore, it delayed the time to reach the peak temperature.

A peak temperature of 45.2ºC was recorded for TSC with OPC grout in 20 h after injection, while 43.0 and 42.1ºC were observed in concrete with 10 and 20% is POFA respectively. A peak temperature of 40.2ºC was, however, recorded for 30% POFA concrete at 28 h after grouting. Both the OPC and POFA grouts ultimately exposed a slow drop in temperature until a relatively steady state was reached during the test. The reduction in the heat of hydration of mixes is attributed to the lower amount of calcium oxide (CaO) due to the replacement of POFA. In terms of peak temperature and the time to reach this temperature, grouts containing POFA performed better than that containing OPC alone. A similar observation has been reported by Awal and Shehu [8], who found a reduction in temperature in concrete containing high volume POFA as compared to that in OPC concrete. The results obtained are also in agreement with Chandara et al. [37], who found that the total heat of hydration of blended cement pastes containing POFA was lower than that of OPC paste.

Table 4 Heat of hydration behavior of two-stage concrete with OPC and various amount of POFA

Properties	OPC	10% POFA	20% POFA	30% POFA
Initial temperature (LC)	28.0	28.2	28.1	27.8
Peak temperature (LC)	45.2	43.0	42.1	40.2
Time since mixing to peak temperature (h)	19.5	22.0	24.0	26.0
Relative reduction in peak temperature (%)	0.0	5.0	7.0	11.0

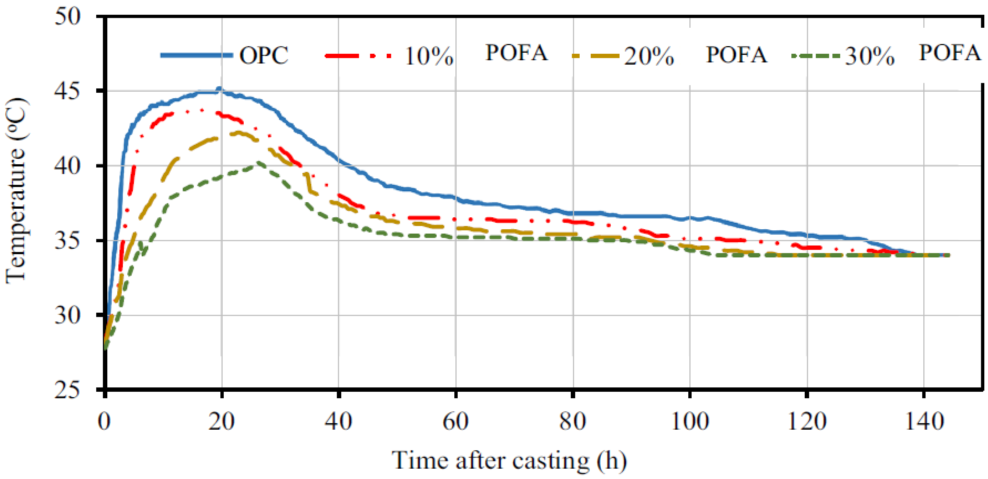

Fig. 8 Development of temperature in two-stage concrete mixes

3.4 Heat transfer

Heat in conduction is transferred from a hot temperature body to a cold body temperature. The transfer of heat will continue as long as there is a difference in temperature between the two bodies. Once the two locations have reached the same temperature, thermal equilibrium is established and the heat transfer stops. Thermal mass is a term that describes the ability of a material to store heat; which various construction materials can do to a greater or lesser extent. Concrete and masonry products do this well and, being dense materials, can also store a lot of heat [9].

In this study the time-temperature behaviour was studied by measuring the temperature at mid depth of concrete specimens during boiling of water (Fig. 4). It has been observed that the temperature of water and TSC specimen with OPC reached to 100ºC almost at the same time at 25 h after the test initiated (Fig. 9). But for concrete samples containing POFA, the rate of heat transfer was found to be lower than that of OPC concrete. It is interesting to note that the effect of high POFA content on the delay of time at which the specimen reached 100ºC was more significant than that of lower POFA content and OPC concrete alone.

Data presented in Fig. 9 further depicts that although the rate of transfer of heat in all the mixes containing POFA was significantly lower, considerably higher rate of heat was evolved in the OPC concrete. A maximum time of 35 h, for example, to reach 100ºC was observed for TSC with 30% POFA; while concrete with 10 and 20% POFA reached the same temperature at 30 h of casting. Two-stage concrete containing POFA, therefore, obtained a better result in terms of delay in heat transfer providing better insulation in concrete structure.

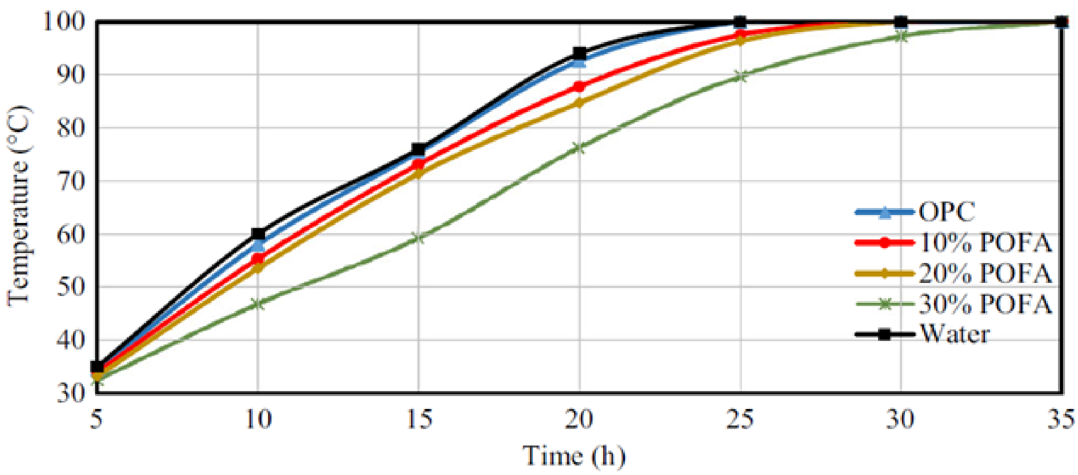

Fig. 9 Influence of POFA content on heat transfer of TSC in boiling water

4. CONCLUSION

Mechanical properties and thermal behavior of two-stage concrete containing POFA has been outlined in this paper. It has been found that the flow properties of grout significantly increased with the inclusion of POFA in the mix. Higher replacement of OPC by POFA resulted in lower bleeding and density of the grout. It has also been found that the grout containing POFA increased the compressive and tensile strength of TSC and these values are higher in concrete made by pump method than that in the gravity one.

The experimental results in this study further demonstrate that POFA has good potentials in controlling and reducing the heat of hydration of TSC. Although, the maximum strength was obtained for 10% POFA replacement, higher volume replacement of OPC by POFA is advantageous, particularly for mass prepacked concrete, where thermal cracking due to extreme heat rise is of great concern. Along with heat of hydration, the rate of heat transfer was also lower in two-stage concrete containing POFA.

5. ACKNOWLEDGEMENTS

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