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Effect of high temperatures on physical and compressive strength properties of self-compacting concrete incorporating palm oil fuel ash

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Abstract. Palm oil fuel ash (POFA) has been widely utilized to replace cement in self – compacting concrete (SCC) to reduce the cost of its production, environmental pollution and health hazard caused in the cement production. However, the effect of high temperatures on SCC incorporating POFA has not been well established. The purpose of this research is to examine effects of high temperatures on the physical and compressive strength properties of SCC incorporating POFA with replacement level of 20% by weight of cement. The compressive strengths of SCC specimens were evaluated at 28 days of curing using both cubes and cylinders. Thereafter, the SCC specimens were exposed to high temperatures of 200, 400, 600 and 800 °C using an electric furnace for a period of 2 hours after attaining the required temperatures. After exposure, mass losses together with residual compressive strength were determined. The results of the test showed that there was a continuous reduction in mass of the specimens with increase in temperature. The results also revealed that the colour of the specimens does not change at 200 °C but the colour changes started to occur between 400 °C up to 800 °C. There was an increase in the residual compressive strength for the two mixes at temperature range of 200 – 400 °C for the cubes and cylinders whereas at the temperature of 400 – 600 °C and 600 – 800 °C, there was a sharp reduction in the residual compressive strength for the two mixes for the cubes and cylinders. The SCC with and without POFA follow the same trends.

1. Introduction

Utilization of self – compacting concrete (SCC) offers numerous benefits to construction practice such as noise reduction, elimination of compaction, enhanced homogeneity, reduction in construction time, and outstanding surface quality [1]. However, the use of expensive chemical admixtures and cement in large amount is essential in the production of SCC to enhance the filling ability, the passing ability and segregation resistance [2]. Due to these two important attributes, it makes the cost of the SCC to be higher and at the same time making the carbon dioxide (CO_2) emissions to be higher. According to Benhelal et al. [3], for every 1 tonne of cement produced gives out an approximately 0.9 tonne of CO_2. Rashad and Sadek [4] reported that apart from CO_2, there are gases like sulphur (iv) oxide (SO_2) and nitrous oxide (NO_x) that are released from the cement manufacturing that can cause the acid rain and greenhouse effect.

One possible option to lessen the cost of SCC is the usage of mineral additives such as ground granulated blast furnace slag (GGBFS), fly ash (FA), natural pozzolans, and palm oil fuel ash (POFA) which are finely ground materials and mixed to concrete as different constituents either before or during mixing [2,5,6]. As these mineral additives substitute part of the cement, the cost of SCC will

be lowered particularly when the mineral additive is an agro - industrial by - product or waste [2]. Among these materials, palm oil fuel ash, a waste material gotten from burning palm kernel shells and palm oil husks as fuel in palm oil mill boilers [7], has been described to enhance the durability and mechanical properties of SCC when utilized as a supplementary cementing material [8].

The plantation of oil palm tree (*Elaeis guineensis*) started in Malaysia as far back in 1960 with 54,000 hectares which later increased to 1.02 million hectares in 1980 and 2.03 million hectares in 1990. The area used for the plantation is increasing progressively every year. In 1995, it increased to 2.54 million hectares and 4.05 million hectares in 2005 while the plantation increased to 5.64 million hectares in 2015. The area for the plantation continued to increase with 5.74 million hectares in 2016, 5.81 million hectares in 2017 and presently it is 5.85 million hectares in 2018 according to Malaysian Palm Oil Board [9]. As at now palm oil is the mainstay of the economic growth of Malaysia. As the plantation of oil palm tree increased, the wastes generated in the palm oil industry will also increase.

The effect of elevated temperatures on the properties of concrete containing POFA have been studied widely [7,10,11]. All the authors concluded that POFA concrete performs better at high temperatures than the concrete without POFA. Though concrete with and without POFA experiences progressive changes in terms of colour, loss of mass, formation of cracks and strength reduction. Moreover, the effect of elevated temperatures on the properties of SCC containing mineral additives apart from POFA, such as fly ash [12], GBFS and fly ash [13] and limestone powder, basalt powder and marble powder [14] have been studied extensively. All the authors reported that there is a reduction in the mass of the SCC after exposed the specimens to elevated temperature. However, there are conflicting results on the residual compressive strength of the SCC. Pathak and Siddique [12] reported that between the temperature ranges of 20 - 200 ℃, there is a small reduction of strength whereas between the temperature ranges of 200 - 300 ℃, the strengths of entire SCC mixes slightly enhanced as related to the strength at 100 ℃. In contrary to this, Uysal [14] and Uysal et al. [13] reported that between the temperature ranges of 20 - 200 ℃, there is a small increase in strength whereas between the temperature ranges of 200 - 400 ℃, the strengths of entire SCC mixes decreased.

The properties of SCC containing POFA when exposed to high temperature are scarce in the literatures. Up till date, it was only Alsubari et al. [15] that extends part of its research to the residual compressive strength of SCC incorporating 30, 50 and 70% modified treated POFA (MT – POFA). The cube specimens produced were exposed to elevated temperature in an electric furnace at 100, 400 and 600 ℃ for a period of 60 minutes after reaching the required temperature. In order to accept the use of POFA self – compacting concrete globally, the properties of fire - damaged SCC should be studied further so as to understand the behavior of SCC containing POFA. In view of this, study of the properties of SCC containing POFA when exposed to more different high temperatures are important to be carried out. The main objective of this investigation was to study the effects of high temperatures on the mass loss, discolouration, cracking patterns and the residual compressive strength of SCC incorporating POFA. The SCC specimens were exposed to different temperatures of 200, 400, 600 and 800 ℃ for a period of 2 hours.

2. Experimental Procedures

2.1 Materials

The materials used in this study were ordinary Portland cement (OPC), POFA, dry river sand with nominal maximum size of 4.75 mm as fine aggregate, crushed granite with nominal maximum size of 10 mm as coarse aggregate, a polycarboxylic based superplasticizer of trade name SIKA VISCOCRETE – 1600 and normal tap water.

The POFA used was obtained from Alif Palm Oil Mill factory located in Kota Tinggi of Johor, Southern State of Malaysia. The raw POFA collected was then dried in an oven at a temperature of 110 °C for 24 hours in order to remove the moisture on it since the POFA was kept in an open area after production. Thereafter, the dried POFA was sieved through a 300 μm sieve in order to eliminate

large particles and other contaminations as well as to decrease the carbon content to avert glassy phase of crystallization and agglomeration of particles [16]. Los Angeles milling machine was later use to grind the sieved burned ash to lessen the particle size in order to increase its fineness. Both eleven stainless steel balls of diameter 32 mm with total weight of 4.16 kg and 4 kg of the sieved burned POFA were then put together in the revolving cylinder. For every grinding, the drum of the machine was set to rotate at a velocity of 32.4 rpm by means of an electric motor. The POFA fineness was examined every 4 hours by wet sieving using a 45 μm sieve in line with the procedure in ASTM C430-08 [17]. After 20 hours of grinding, the quantity passing 45 μm sieve reached 95% which is more than 66% recommended by ASTM C618-08a [18]. The physical properties and oxide compositions of POFA and OPC are shown in Tables 1 and 2, while the physical properties of river sand and crushed granite is presented in Table 3.

Table 1. Physical Properties of palm oil fuel ash and ordinary portland cement.

Property	POFA	OPC
Specific Gravity	2.42	3.15
Loss on Ignition (%)	11.7	3
BET Fineness (m^2/g)	38.37	1.25
Colour	Dark Gray	Gray

Table 2. Oxide compositions of palm oil fuel ash and ordinary portland cement.

Compound (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	MnO	K_2O
POFA	43.9	4.32	4.79	8.66	3.1	1.04	0.06	10.8
OPC	16.2	3.52	2.91	70.9	0.76	3.36	0.13	0.57

Table 3. Physical properties of river sand and crushed granite.

Aggregates Type	D_{max} (mm)	FM	Specific Gravity
River Sand	4.75	3.1	2.55
Crushed Granite	10	6.3	2.56

D_{max} : maximum aggregate FM : modulus of fineness

2.2 Mix Proportions

The mixture proportions of the SCC were determined according to the EFNARC specifications and guidelines for SCC [19]. The mix designs used for the production of SCC is presented in Table 4. Sika ViscoCrete – 1600 brand of polycarboxylic based HRWR obtained from Sika Kimia Sdn Bhd, in Malaysia was utilized as superplasticizer (SP) in the SCC mixtures in order to obtain the fresh properties.

2.3 Preparation of Specimen and Testing Method

Coarse aggregate then follow with fine aggregate were first put into the rotating drum of the concrete mixer machine and mixed for 1 minute. Then, 25% of the mixing water was added to the aggregates and mixed for 2 minutes to damp the aggregates adequately. The concrete mixer was then switched off to allow resting for 3 minutes, in order to allow the aggregates to engross water needed for saturation. This step was carried out so as to circumvent the immersion of the SP by the aggregates. Subsequently, the binding materials (cement alone or incorporating POFA) was added to the wet aggregates in the concrete mixer. Straightaway, the power of the concrete mixer was on and the

mixing process was sustained for another 2 minutes with the addition of the 50% of the mixing water. Then part of the remaining 25% of the mixing water was added to the HRWR dosage in the ratio of 1 : 1. The SP solution was later added to SCC mix in the mixer and the mixing was sustained for 3 minutes [20]. Thereafter, the remaining part of the 25% of the mixing water left was finally added to SCC mix while the mixing was sustained for 3 minutes.

Immediately after the completion of the mixing, the fresh concrete were sampled and verified in conformity with specifications of EFNARC [19] for flow ability, filling ability and passing ability tests. All these tests must be carefully maintained in order to achieve the required SCC. After determining the fresh properties, the fresh SCC mixes were then poured into 100 x 100 x 100 mm cube and 100 x 200 mm cylinder steel moulds and kept for 24 hours in an ambient condition. Thereafter, the samples were removed from the moulds and cured in water at 26 ± 3 °C until the testing period. Cylinder and cube moulds were used to assess the compressive strength of the SCC.

Table 4. Mix proportions of SCC incorporating palm oil fuel ash.

Mix No	POFA (% of B)	W/B Ratio	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Cement (kg/m^3)	POFA (kg/m^3)	Water (kg/m^3)	HRWR (% of B)
SCC0	0	0.4	780	870	460	0	184	2.5
SCC20	20	0.4	780	870	368	92	184	2.8

2.4 Heating of SCC Specimens

Before the heating operation commences, all the specimens were weighed and the value of their weight were recorded. The value of the temperature of the surrounding was also recorded. Thereafter, the compressive strength of the specimens cast with and without POFA which serve as a control were determined at ambient temperature of 27 °C. The remaining specimens were exposed to heat treatment in an automatic regulated electric furnace to required temperature levels of 200, 400, 600 and 800 °C. The heating rate used was 2.7 °C/min. When the required temperature was attained, the temperature was then maintained for a period of 2 hours. This process is aimed at simulating the exposure conditions of real life structures [11]. At the end of the heating procedure, the electric furnace was switched off while the SCC specimens remained in the furnace in order to cool down to ambient temperature. The process is aimed at avoiding thermal shock on the specimens [7,21].

3.0 Results of the test and discussions

3.1. Properties of POFA

The colour of POFA used is dark grey and this is due to the increasing the sizes of unburned carbon through grinding [10]. The physical properties together with oxide composition of POFA are shown in Tables 1 and 2. It can be observed from the Tables 1 and 2 that POFA possess lower specific gravity and higher loss on ignition than OPC. The chemical composition reveals that the major component of POFA is silicon dioxide or silica (SiO_2). The mass content of silica was 43.9%. This is the main oxide component that contributes to the pozzolanic reaction or secondary hydration in concrete containing pozzolanic material such as POFA. There were other important oxides such as Aluminium oxide (Al_2O_3) and Iron oxide (Fe_2O_3) in reasonable amounts. It also possesses low content of calcium oxide (CaO) which is about 8.7% compared to cement which is 71%. Due to the fact that the oil palm trees consume a lot of Potassium oxide (K_2O) from the soil during its cultivation period [22], the POFA has higher value of 10.8% for K_2O compare to cement which is less than 1%. It has a combined (SiO_2 + Al_2O_3 + Fe_2O_3) content of 53.01%. According to ASTM C618 [18], the minimum amount of combined (SiO_2 + Al_2O_3 + Fe_2O_3) required for class – C pozzolan is 50%. Therefore, POFA used for

the study was classified as equivalent to class – C and thus found suitable for the production of SCC. The result obtained for combined (SiO_2 + Al_2O_3 + Fe_2O_3) is in the range with the results obtained by Mohd Ariffin etal. [23] and Yusuf et al. [24] in which their results are 56.5% and 51.55%. The reasons for different values of the combined SiO_2, Al_2O_3 and Fe_2O_3 content of POFA are due to particle fineness, parts of the oil palm tree charred, temperature used for burning etc [22].

3.2. Fresh Properties of SCC

The results of various fresh properties carried out on SCC using slump flow test (slump flow and T_{500mm}), V – funnel flow time and L – box passing ratio for the two mixes are presented in Table 5. The slump flow test is used to assess the flowability and the flow rate of SCC in the absence of obstructions [19]. The slump flow of the two mixes was 670 mm and 690 mm and the time taken to spread to the diameter of 500 mm for the two mixes were 2.15 and 2.43 s, as shown in the Table 5. The two fresh mixes of the SCC satisfied the basic slump flow requirements as specified by EFNARC [19] for slump class SF2 for slump flow greater than 650 mm. Due to the addition of POFA, the quantity of HRWR used in the mix is increased and this make the value of slump flow to increase. The result of slump flow obtained is also in line with the result obtained by Alsubari et al. [25] and Salam et al. [5].

The V – funnel flow time (T_V) of the two SCC mixes as presented in Table 5 are 8.50 and 10.15 s. The values obtained are greater than 8 s as recommended by EFNARC [19]. Therefore, the two SCC mixes could be classified as concretes in the viscosity class VF2. When POFA was added to the mix, the value of T_V time was increased. The increase in T_V time indicates that the plastic viscosity of the concrete increased with addition of POFA. The result of V - funnel flow time obtained is also in line with the result obtained by Mohammadhosseini et al. [26] and Ranjbar et al. [8]. The result of the L – box passing ratio is shown in Table 5. The values are 0.83 and 0.85 for 0% and 20% of POFA replacement. When POFA was added to the mix, the value of passing ratio (PR) was increased. This is due to the fact that POFA had increased of volume paste and reduced aggregate content which contributed to upholding good passing ability [27]. The values for L – Box passing ratio specified by EFNARC [19] for the passing ability under class of PA2 are range from 0.8 to 1.0. As a result, the two SCC mixes had a good passing ability.

Table 5. Results of the filling ability and passing ability.

Mix No	Filling ability		Passing ability	
	Slump flow (mm)	T500mm slump flow time (s)	V - funnel flow time (s)	L - Box passing ratio (PR)
SCC0	670	2.15	8.5	0.83
SCC20	690	2.43	10.15	0.85

3.3 Effect of High Temperature on the Mass of SCC

Effect of high temperature on the mass loss of SCC with and without POFA is shown in Figure 1. When the temperature of the furnace increased, there is a continuous reduction in the mass of SCC with and without POFA. It can be observed from the Figure 1 that the higher the temperature of exposure, the larger was the mass loss of the test specimens. The mass loss between ambient temperature (27 °C) and 200 °C was very small for control SCC and SCC containing 20% POFA. The loss of mass in this temperature range is attributed to the transfer of moisture from the surfaces of the concrete to the surrounding environment [7]. When the heating begins, the free water in the concrete migrates towards its outermost layers and lastly escapes in the form of vapour [11].

As soon as the temperature of the furnace increased from 200 °C to 400 °C, there was a rapid mass loss of 5.8% and 6.38% for control SCC and SCC with 20% POFA. The rapid loss of mass between 200 °C and 400 °C was accredited to the loss of water from the desiccation of the calcium silicate hydrate and loss of free water contained in the capillary pores [28]. As the temperature of exposure

increases to 600 °C, the mass loss for the two mixes continued to increase as well in such a way that the values were 7.08% and 7.92%, for 0% and 20% POFA concrete. However, the rate at which the concrete mass loss occurred was slowed down when the temperature was increased from 600 to 800 °C. In this temperature range, the values of mass loss were 7.88% and 8.86% for 0% and 20% POFA concrete. Generally, the mass loss by SCC containing POFA at all the temperatures of exposure was higher than that noticed in control SCC, possibly as a result of higher humidity content withheld by the particles in POFA [11].

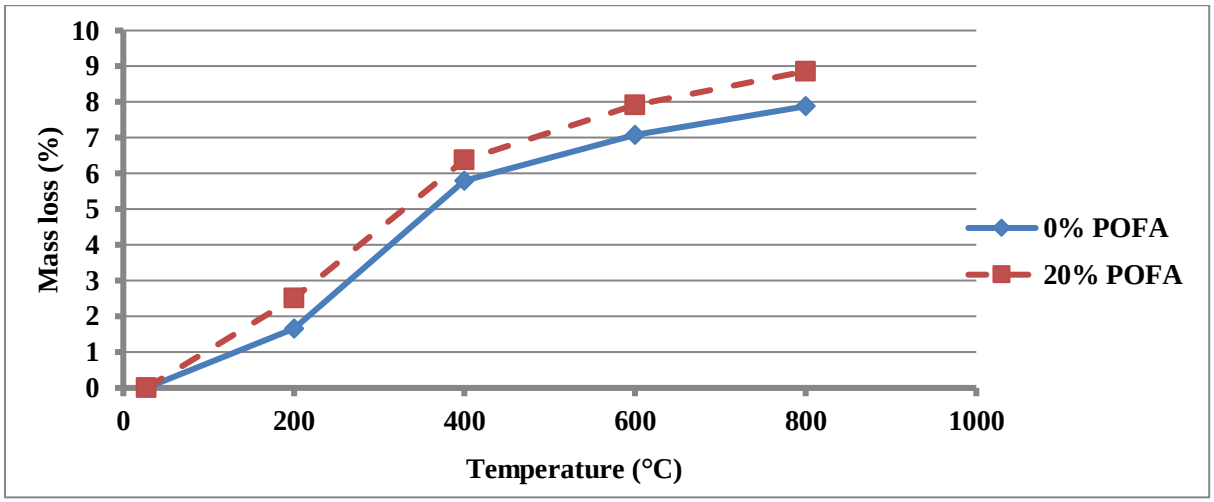

Figure 1. Effect of high temperature on the mass of SCC cube with and without POFA.

3.4 Effect of High Temperature on Discolouration

When the specimens were exposed to 200 °C, the colour does not change. That is the colour of control SCC was grey while the colour of SCC with POFA was black. However, the colour of the control SCC was changed from grey to dark grey at 400 °C while the colour of SCC changed from black to light black. As soon as the temperature increased from 400 to 600 °C, the colour of the control SCC changed to light grey whereas the SCC with POFA changed to dark grey. At 800 °C, the colour of the control SCC was changed to whitish grey colour, while the SCC with POFA changed to brownish grey colour. With the results obtained, colour of SCC surface can be used to evaluate the temperature exposure intensity and duration to which it has been subjected [15]. Ismail et al. [11] and Alsubari et al.[15] stated that assessing the surface colour changing of concrete exposed to high temperatures can be a practical benefit to get a preliminary assessment and provide a sign of the strength of temperature exposure and comparable duration to which it has been subjected.

3.5 Effect of High Temperature on Cracks

Visual inspection was carried out to know the way the cracking occurs on the surface of the heated SCC specimens with and without POFA. At temperature of 200 and 400 °C, no visible cracking was noticed on both the control SCC and SCC incorporating POFA. As soon as the temperature was increased from 400 to 600 °C, hairline cracks start to appear and continued to increase further as the temperature was increased to 800 °C. Infacts, both the control SCC and SCC incorporating POFA have similar cracks pattern behaviour. Throughout the heating period for all the specimens, no spalling was observed. Alsubari et al. [15] reported that the development of the cracks on the surface of the concrete was accredited to the disintegration of $[Ca(OH)_2]$ to form CaO and its resulting process with the humidity from the environment air during cooling appears to produce micro - cracks as a result of the increase in volume connected with these process [29].

3.6 Residual Compressive Strength

The cube and cylinder residual compressive strength of the SCC with and without POFA after being exposed to different temperatures are shown in Figures 2 and 3. At ambient temperature, the values of the compressive strengths for control SCC were 5.2% and 3.3% higher than SCC with POFA for cube and cylinder. However, researchers have reported that the highest 28 days compressive strength in POFA self - compacting concrete was established to be 20% replacement level of POFA [27,30,31]. This may be due to the lower silicon dioxide (SiO_2) content of the POFA used in this study (43.9%) when compared to the studied carried out by Safiuddin et al. [27] and Salam et al. [31], in which SiO_2 was around 63%. Galau and Ismail [32] reported that compressive strength of concrete incorporating POFA with higher silica content was better compared to concrete incorporating POFA with lower silica content.

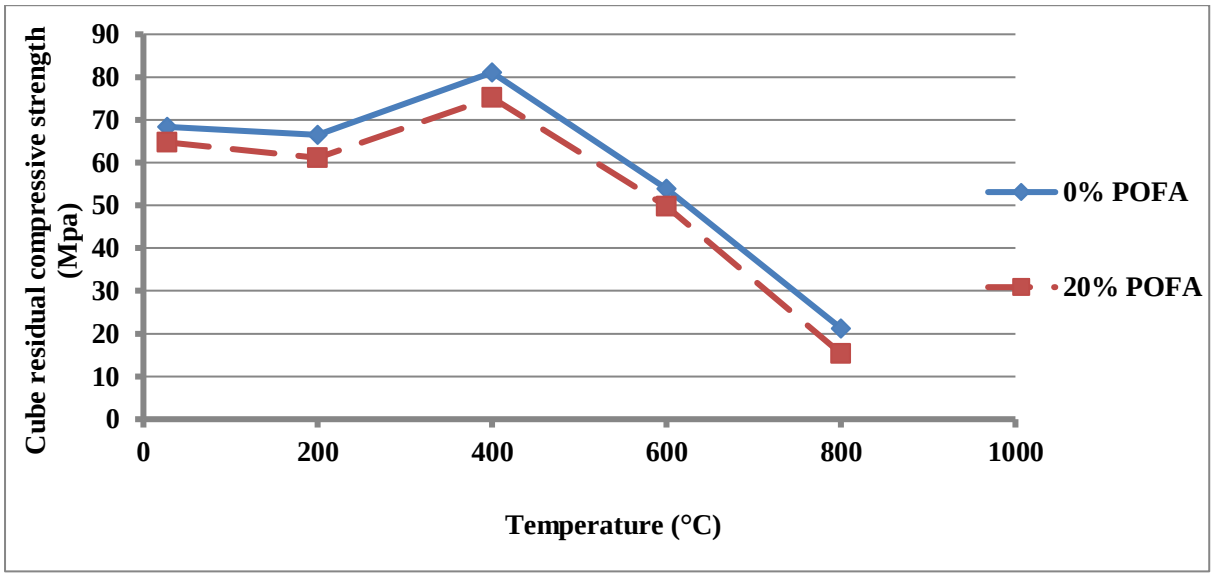

Figure 2. Cube residual compressive strength of SCC with and without POFA.

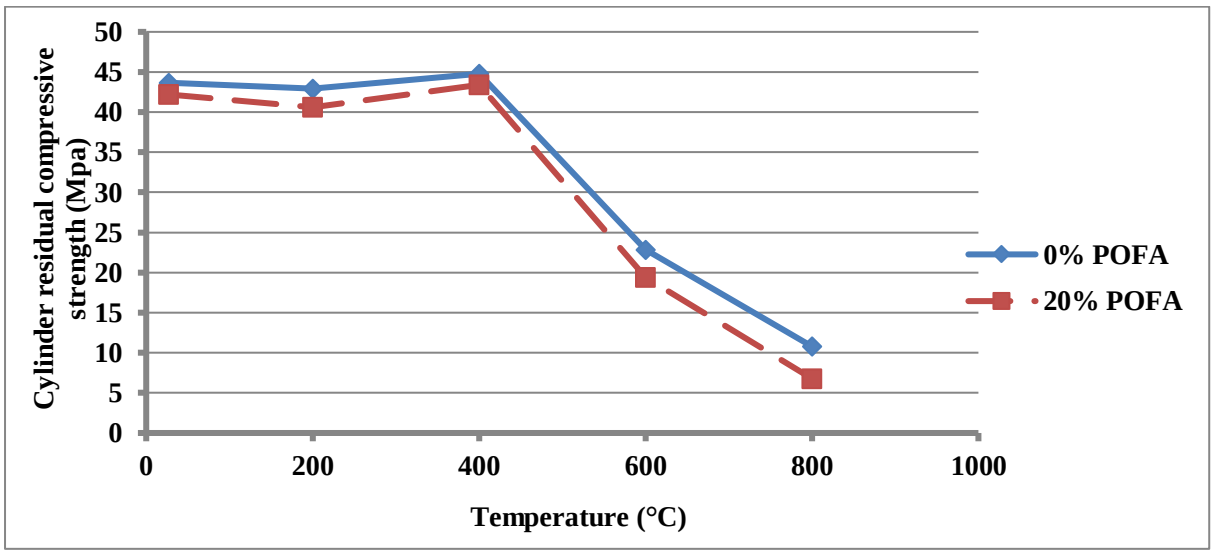

Figure 3. Cylinder residual compressive strength of SCC with and without POFA.

In view of the value of residual compressive strength gotten at high temperatures for the cube and the cylinder, the effect of temperature is classified into four temperature phases, viz., phases 1, 2, 3 and 4 with temperature in the range of 27–200 °C, 200–400 °C, 400–600 °C and 600–800 °C, correspondingly. In the first phase, the cube and cylinder residual strength was decreased slightly for the SCC with and without POFA. However, the SCC with and without POFA retained approximately 94% and 97%, respectively; and 96% and 98%, respectively of their initial strength for the cube and cylinder. The reduction in the residual strength is accredited to gradual desiccation inside the cement matrix, therefore altering the physical physiognomies of concrete from a soaked surface dry state to a dry state [7].

In the second phase, there was a sharp increment in the residual strength of approximately 16% and 19% for SCC with and without POFA, in comparison with reference strength verified at the same days of curing without heating of the cube. However, for the cylinder, it increased slightly with the value of 2.8% and 2.6%, respectively for the SCC with and without POFA**.** The increase in compressive strength in second phase for SCC without POFA is accredited to the overall stiffening of cement paste or the increase in forces at the surface between paste particles owing to the elimination of absorbed moisture [33]. According to Alsubari et al. [15], the improvement in the compressive strength for SCC with POFA was attributed to the development of extra hydration products by converting calcium silicate hydrate phase to form tobermorite phase which is 2 – 3 times stronger than the C – S – H [21]. This increase in compressive strength was also noticed by Alsubari et al. [15].

In the third phase of the temperature range, there was a severe decrease in the residual strength for the two mixes. However, the SCC with and without POFA retained approximately 77% and 79%, respectively; and 54% and 45% of their initial strength for the cube and cylinder. The severe reduction in the strength is attributed to the roughening of the pore - structure of the hardened cement paste [21]. The results obtained is also in line with the findings of Alsubari et al. [15] and Uysal et al. [13].

In the last phase of the temperature range (600 – 800 °C), there exist a sharp reduction in the residual compressive strength for the two mixes. The SCC with and without POFA retained approximately 24% and 27%, respectively; and 25% and 16%, respectively of their initial strength for the cube and cylinder. The sharp reduction in the residual strength is attributed to the contraction of cement paste and expansion of aggregates that occurred and as a result of this; higher stress concentrations are formed in the transition zone and thus affects the bonding between the cement paste and aggregate [13]. A similar result was observed by Uysal et al. [13] in which the concrete retained 22% of its strength at ambient temperature.

4.0 Conclusions

The effects of high temperatures on physical and compressive strength properties of self – compacting concrete incorporating 20% palm oil fuel ash were investigated. The following conclusions were made based on the experimental results gotten from the study.

- There was a continuous reduction in mass of the SCC specimens with increase in the temperature. The reduction was very sharp between 200 and 400 °C and less than 8% and 9% at 800 °C for control SCC and SCC with POFA.
- The colour of the specimens does not change at 200 °C but the colour changes started to occur between 400 °C up to 800 °C. Brownish grey colour and whitish grey colour was observed for SCC with and without POFA at 800 °C.
- The surface cracks on the specimens were noticed at 600 °C and continued to increase further at 800 °C for the two mixes.
- Between the temperature of 28 and 200 °C, the SCC with and without POFA retained approximately 94% and 97%, respectively; and 96% and 98%, respectively of their initial compressive strength for the cube and cylinder. However, between the temperature of 200 and 400 °C, there was a sharp increase in the residual strength of approximately 16% and 19%, respectively and 2.8% and 2.6%, respectively for SCC with and without POFA, in

comparison with reference compressive strength verified at the same days of curing without heating for the cubes and cylinders.

- Between the temperature of 400 and 600 °C, the SCC with and without POFA retained approximately 77% and 79%, respectively; and 54% and 45% of their initial strength for the cubes and cylinders. Nevertheless, at temperature range of 600 and 800 °C, there was a sharp reduction in the residual strength for the two mixes. The SCC with and without POFA retained approximately 24% and 27%, respectively; and 16% and 25%, respectively of their initial strength for the cube and cylinder.

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