Palm oil fuel ash as partial substitute to cement in concrete: performance at elevated temperatures

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Abstract. In this paper, the palm oil fuel ash (POFA) concrete is produced using POFA as partial replacement to ordinary Portland cement (OPC 53 grade) (0%-P0, 20%-P20, 40%-P40 and 60%-P60) by weight. The POFA concrete specimens are subjected to elevated temperatures of 200 °C, 400 °C and 800 °C for duration of 2 hours. The compressive strength, ultrasonic pulse velocity (UPV) and mass loss (%) of POFA concrete are evaluated. The results indicate that the compressive strength is enhanced by the use of POFA in concrete. At elevated temperatures, POFA concrete showed higher resistance than P0 concrete (control concrete) and P20 concrete showed best performance in POFA concrete, when subjected to elevated temperatures. From the experimental results, it can be observed that 20% POFA can be used as partial replacement to cement in producing sustainable concrete.

Keywords: Concrete, Elevated Temperatures, Palm oil fuel ash, Sustainable Concrete.

1. Introduction

Structural elements when effected by elevated temperatures or fire accidents is a severe problem. Concrete is considered as an incombustible material, but when subjected to higher temperatures or fire accidents, its constituents will be affected, resulting in the worsening of its properties and performance [1]. At elevated temperatures, the performance of concrete is inclined by the mix proportion, size and shape of members, thermal compatibility of constituents, and type of aggregates and exposure duration of target temperature. The degradation of concrete at fire accidents and or elevated temperatures includes causing of spills, crack formations, reduction of cohesiveness between concrete constituents and large pores[2]. The thermal properties such as conductivity, diffusivity, coefficient of thermal expansion and specific heat are comparable to both nominal and high strength concrete. The spalling nature of concrete is influenced by the free water and moisture content. Furthermore, at elevated temperatures, the dense microstructure concrete or high-performance concrete with zero moisture will spall. The changes that occur in concrete when exposed elevated temperatures are: (1) at 100°C, free water in concrete evaporates. (2) at above 180°C, the calcium silicate dehydrates. (3) between 400°C and 900°C, the dissociation of calcium hydroxide takes place. (4) at above 900°C, complete deterioration and spalling of concrete occurs [3-4].
A huge amount of waste materials and by-products in the size of fines are used as mineral filler or supplementary cementitious materials (SCMs) in enhancing the properties of concrete. At present, the global annual production of solid waste material is about 1.3 billion tonnes and is expected to reach 2.2 billion tonnes by 2025 [5]. Sustainability in concrete production is the major reason for the enhanced use of filler materials or SCMs as alternative binder materials. Partial replacement of cement in concrete by agricultural by-products or by industrial by-products which may act as fine fillers as well as pozzolanic materials can reduce the cement consumption in concrete production which may lead to the reduction of greenhouse gases emission by the cement industries and will result in both economic and environmental benefits. SCMs may be classified as natural pozzolans, artificial pozzolans and non-pozzolanic fillers. Many researchers used the SCMs as partial substitute of cement and found enhancement in properties of concrete such as:

(a) Reducing thermal shrinkage and heat of hydration
(b) Reducing alkali-aggregate reaction
(c) Increasing water-tightness
(d) Enhancement in resistance to acid attack
(e) Lowering vulnerability to leaching and dissolution
(f) Decreasing cost of concrete production

Numerous studies have been carried out by researchers on the use of various fillers as SCMs. The addition of fillers will have a chemical impact on cement hydration. The use of fillers expands the cement matrix volume and compensates the irregularity of coarse aggregate filling in concrete. Concrete produced with non-pozzolanic fillers has no negative effect on the strength properties when compared with pozzolanic fillers modified concrete. Moreover, concrete with non-pozzolanic fillers exhibited more resistance to segregation and bleeding than pozzolanic fillers. SCMs usage in concrete improves the microstructure of concrete and reduces the heat of hydration, leading to the enhancement of mechanical and durability properties. Still there is a need to search for alternative materials and an extensive research is to be done to address the nature of alternative materials and to use them in producing sustainable and cost-effective concrete [6-8]. The present paper aims to produce a green concrete by replacing cement with POFA and also to study the effect of targeted temperatures on compressive strength, UPV and mass loss (%) of POFA concrete. The elevated temperatures considered are 200°C, 400°C and 800°C for duration of 2 hours.

2. Materials and Methods

OPC 53 grade cementis used for producing concrete mix.Krishna river sand and coarse aggregate of maximum size 20 mm are used for concrete mixing. The M30 grade concrete (control concrete: P0) mix arrived at was 1:1.59:3.27 (Cement: Fine aggregate: Coarse aggregate), in accordance to IS 10262: 2009 [9]. OPC was partially substituted with POFA (20%-P20, 40%-P40 and 60%-P60) by weight, for casting M30 grade concrete. The water to binder ratio considered is 0.4. Table 1 details the concrete mix proportions. The concrete constituents are mixed uniformly by using a pan mixer and mixed thoroughly to achieve uniformity. The fresh concrete is transferred into cubes of size 100 mm in accordance to IS 516: 1959 [10] and then cured for 28 days. Both control concrete (0% POFA) and POFA concrete are left free in the laboratory for 7 days and then heated to the target temperatures by using an electrically controlled furnace (capacity of 1200 °C) for obtaining the compressive strength, mass loss (%) and UPV of specimens exposed to targeted temperatures.

The elevated temperatures considered are 200 °C, 400 °C and 800 °C and the exposure duration is of 2 hours. The heating rate of target temperatures is kept at 10 °C /min [11] for maintaining the thermal stability of inner and outer portion of concrete specimens. The electric supply of the electrically operated furnace is turned off after achieving 2 hours of exposure duration and then the specimens were left undisturbed for 24 hours. Fig.1 shows a view of POFA used for the experimental study. Fig. 2 shows the image of furnace control of achieving the target temperatures of 200°C and 400°C.
Figure 1. A view of POFA used for the experimental study.

Figure 2. Image showing the achieved target temperatures of 200°C and 400°C.

Table 1. Details of mix proportions

| Mix designation | Cement (kg/m³) | POFA (%) | POFA (kg/m³) | Fine aggregate (kg/m³) | Coarse aggregate (kg/m³) |
|-----------------|----------------|----------|--------------|------------------------|--------------------------|
| P0              | 410            | 0        | 0            | 652                    | 1341                     |
| P20             | 328            | 20       | 82           | 652                    | 1341                     |
| P40             | 246            | 40       | 164          | 652                    | 1341                     |
| P60             | 164            | 60       | 246          | 652                    | 1341                     |
3. Results and Discussion

3.1 Compressive strength of POFA concrete:

Table 2: Compressive strength of POFA concrete exposed to 200 °C

| Mix designation | POFA (%) | Average Compressive strength (MPa) | Average loss (%) of $f_c$ after exposed to 200°C |
|-----------------|----------|------------------------------------|-----------------------------------------------|
|                 |          | $f_c$ @ 28 days (Ambient) | $f_c$ after exposed to 200°C |                       |
| P0              | 0        | 48.98                             | 43.24                                         | 11.72                |
| P20             | 20       | 42.30                             | 37.44                                         | 11.49                |
| P40             | 40       | 38.45                             | 32.67                                         | 15.03                |
| P60             | 60       | 29.50                             | 22.11                                         | 25.05                |

Table 3: Compressive strength of POFA concrete exposed to 400 °C

| Mix designation | POFA (%) | Average Compressive strength (MPa) | Average loss (%) of $f_c$ after exposed to 400°C |
|-----------------|----------|------------------------------------|-----------------------------------------------|
|                 |          | $f_c$ @ 28 days (Ambient) | $f_c$ after exposed to 400°C |                       |
| P0              | 0        | 48.98                             | 29.43                                         | 39.91                |
| P20             | 20       | 42.30                             | 26.51                                         | 37.33                |
| P40             | 40       | 38.45                             | 23.38                                         | 39.19                |
| P60             | 60       | 29.50                             | 16.54                                         | 43.93                |

Table 4: Compressive strength of POFA concrete exposed to 800 °C

| Mix designation | POFA (%) | Average Compressive strength (MPa) | Average loss (%) of $f_c$ after exposed to 800°C |
|-----------------|----------|------------------------------------|-----------------------------------------------|
|                 |          | $f_c$ @ 28 days (Ambient) | $f_c$ after exposed to 800°C |                       |
| P0              | 0        | 48.98                             | 9.53                                          | 80.54                |
| P20             | 20       | 42.30                             | 7.34                                          | 82.65                |
| P40             | 40       | 38.45                             | 6.42                                          | 83.30                |
| P60             | 60       | 29.50                             | 4.66                                          | 84.20                |

At ambient temperature, POFA concrete showed higher compressive strength values than P0 concrete, satisfying the provisions of IS 10262:2009 [9]. Tables 2 to 4 shows the compressive strength of POFA concrete at ambient and at target elevated temperatures. Even at P40 concrete also showed acceptable compressive strength value, in accordance to IS 10262: 2009. A highest reduction in the compressive strength is observed at 800°C. In brief, after exposure to targeted temperatures, POFA concrete showed a gradual decrease in compressive strength. Between 200 °C and 400 °C, the reduction in the compressive strength of POFA concrete could be due to the continuous dehydration of cementitious material, thus forming dry state POFA concrete. Between 400 °C and 800 °C, the chemical phase change of Ca(OH)₂ to CaO and at above 573 °C, decomposition of CSH gel takes place and causes further loss of compressive strength. At 800 °C, POFA concrete experiences high expansion of concrete constituents and also suffers physico-chemical change that results in the development of new re-crystallized composites. The results of POFA concrete revealed that the use of POFA as substitute
for OPC will reduce the compressive strength of concrete. Fig. 3 shows the variation of compressive strength of POFA concrete.

![Figure 3. Compressive strength of POFA concrete with effect of elevated temperatures](image)

### 3.2 Mass loss

| Mix designation | POFA (%) | @ 200 °C | @ 400 °C | @ 800 °C |
|-----------------|----------|----------|----------|----------|
| P0              | 0        | 2.82     | 4.63     | 9.37     |
| P20             | 20       | 2.99     | 5.54     | 9.68     |
| P40             | 40       | 3.31     | 5.73     | 10.21    |
| P60             | 60       | 3.62     | 6.27     | 11.14    |

Table 5 shows the variation of mass loss (%) of POFA concrete cubes after exposed to targeted temperatures. The highest mass loss (%) is observed with P60 POFA concrete. An average mass loss (%) of 5.60%, 5.64%, 6.07%, 6.41% and 7.01% are observed with P0, P20, P40 and P60 concretes, respectively. The mass loss at elevated temperatures of POFA concrete could be due to the loss of free and chemically bounded water.

### 3.3 Ultrasonic pulse velocity

| Mix designation | POFA (%) | UPV @ 28 days | UPV after exposed to 200°C |
|-----------------|----------|---------------|---------------------------|
| P0              | 0        | 4.63 (E)      | 4.36 (G)                  |
| P20             | 20       | 4.55 (E)      | 4.23 (G)                  |
| P40             | 40       | 4.12 (G)      | 3.82 (G)                  |
| P60             | 60       | 3.86 (G)      | 3.44 (M)                  |
Table 7. Variation of UPV values of concrete at ambient and at 400°C target temperatures

| Mix designation | POFA (%) | UPV values @ 28 days | UPV after exposed to 400°C |
|-----------------|----------|----------------------|--------------------------|
| P0              | 0        | 4.63 (E)             | 3.34 (M)                 |
| P20             | 20       | 4.55 (E)             | 3.14 (M)                 |
| P40             | 40       | 4.12 (G)             | 2.53 (D)                 |
| P60             | 60       | 3.86 (G)             | 2.24 (D)                 |

Table 8. Variation of UPV values of concrete at ambient and at 800°C target temperatures

| Mix designation | POFA (%) | UPV values @ 28 days | UPV after exposed to 400°C |
|-----------------|----------|----------------------|--------------------------|
| P0              | 0        | 4.63 (E)             | 1.46 (D)                 |
| P20             | 20       | 4.55 (E)             | 1.31 (D)                 |
| P40             | 40       | 4.12 (G)             | 1.22 (D)                 |
| P60             | 60       | 3.86 (G)             | 0.96 (D)                 |

The quality grading and UPV values of POFA concrete, as per IS 13311 (Part 1): 1992[12] are shown in Tables 6 to 8. At ambient temperature, P20 POFA concrete showed excellent UPV values. Even for P60 concrete, good UPV value is observed for POFA concrete. At 200°C, a minimum decrease in the UPV values of POFA concrete is observed. This is due to the evaporation of un-hydrated water that results in the dehydration of cementitious compounds. Fig 4 shows the image of the setup of testing of cubes for UPV values.

Figure 4. Image showing the setup of testing of cubes for UPV values.

At 400°C, a sharp decrease in the UPV values of POFA concrete is observed. This is due to the change in the phase of aggregates and also by the effect of dehydration of CSH gel. At 800°C, the quality of
POFA concrete changed to doubtful and this could be by the complete breakdown of the cement matrix and also due to the dissociation of hardened CSH.

4. Conclusions

From the results of POFA concrete, the following conclusions are made:
1. The use of POFA with 0%, 20%, 40% and 60% as partial substitute for OPC cement in producing concrete showed a slight reduction in the compressive strength.
2. At ambient temperature, P0 concrete showed highest compressive strength.
3. After exposure to temperatures of 200°C, 400°C and 800°C, for POFA concrete, the lowest decrease in compressive strength is observed with P20 concrete and the highest reduction is observed with P60 concrete. This could be due to highest replacement of cement and dilution effect of higher volume replacement of POFA content in the produced concrete.
4. Furthermore, the loss in strength could be due to the change in the chemical composition of POFA concrete at targeted elevated temperatures.
5. The increase in the temperature enhanced the mass loss (%) of POFA concrete and the maximum mass loss (%) is observed with P60 concrete at 800°C.
6. At elevated temperatures, from the results of UPV values it is noticed that up to 200°C, the POFA concrete showed good results and satisfying as per IS 13311 (Part 1): 1992 and P60 showed medium quality concrete.

References

[1] Bahar Demirel, Oguzhan Kelestemur. 2010 Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume, Fire Safety Journal 45 385-39.
[2] N. Venkata Sairam Kumar. 2020 Flexural strength of crushed rock dust concrete at elevated temperatures", IOP Conference Series: Materials Science and Engineering 988.
[3] N. Venkata Sairam Kumar, K.S. Sai Ram. 2019 Performance of concrete at elevated temperatures made with crushed rock dust as filler materials, Materialstoday: Proceedings, Vol: 18(7), pp. 2270-2278.
[4] Aijaz Ahmad Zende, Prof. Kulkarni A.V., Aslam Hutagi. 2013 Behavior of reinforced concrete subjected to high temperatures-A review, Journal of Structural Fire Engineering, 4(4) 281-295.
[5] Antar Choudhary, Vineet Shah, Shashank Bishnoi. 2016 Effect of low cost fillers on cement hydration, Construction and Building Materials 124:533-543.
[6] N. Venkata Sairam Kumar, K.S. Sai Ram. 2018 Sustainable use of waste crushed rock dust in concrete as partial replacement of cement Pollution Research 37(3) 684-689.
[7] N. Venkata Sairam Kumar, K.S. Sai Ram. 2018 Experimental study on properties of concrete containing crushed rock dust as a partial replacement of cement, Materialstoday: Proceedings 5(2.2) 240-7246.
[8] Josephin Alex, J. Dhanalakshmi, B. Ambedkar. 2019 Experimental investigation on rice husk ash as cement replacement on concrete production Construction and Building Materials 127353-362.
[9] IS: 10262-2009. Recommended guidelines for concrete mix design, New Delhi, India: Bureau of Indian Standard.
[10] IS 516-1959. Indian Standard code of practice-methods of test for strength of concrete, New Delhi, India: Bureau of Indian Standards.
[11] Abdullah Hazeyfe Akee, Nilufer Ozyurt Zihnioglu. 2013 High performance concrete under elevated temperatures, Construction and Building Materials 44: 317-328.
[12] IS 13311 (Part 1): 1992. Non destructive testing of concrete-Metho d of test. Part-1 Ultrasonic pulse velocity. New Delhi, India: Bureau of Indian Standards.