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Influence of elevated temperatures on physical and compressive strength properties of concrete containing palm oil fuel ash

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ABSTRACT

The residual compressive strength of concrete containing palm oil fuel ash (POFA) after exposure to elevated temperatures and subsequent cooling was investigated. Specimens from ordinary Portland cement (OPC) and POFA concrete mixes were prepared and subjected to various temperature levels. The POFA concrete contains 20% partial replacement of cement by weight and the temperature levels are; 100, 300, 500 and 800 °C. Two cooling systems which include cooling at room temperature by the natural breeze and water-spray were involved. Compressive strength test was conducted on control specimens as well as concrete specimens revived through the two cooling systems. Physical properties accompanying thermal degradations were also assessed. Residual performance as a ratio of residual strength to original strength was evaluated. The residual performance was found to be higher in POFA concrete than in the normal concrete. In addition, water-cooling was realized to aggravate strength reduction in both normal and POFA concretes when compared with air-cooling. High temperature and cooling system were also found to have great influence on physical properties, such as; mass loss, discolouration and crack patterns.

1. Introduction

The prevailing interest in the use of eco-friendly materials towards improving mechanical and durability properties of OPC concrete may as well require careful assessment on other vital properties such as fire resistance. The issue of fire resistance is very important since structural concrete is required to preserve structural actions over a desired length of time – known as fire rating [1].

Inclusion of eco-friendly materials into OPC mixes originated from the rising concern and worries over environmental degradations such as global warming, atmospheric pollutions and waste disposals. These coupled with the recent worldwide economic recession have indeed strengthened the inspiration for the continuous efforts towards the search for durable and sustainable infrastructures [2,3]. Presently, pozzolans from agricultural waste are receiving more attention since their utilization do not only improve the properties of the blended cement concrete but also reduce the environmental problems [4]. In fact, it has been suggested that POFA can be used as pozzolan in normal and high strength concrete [5,6]. However, depending upon the intended purpose of a structure, materials employed for both normal and high strength concrete must satisfy certain fire resisting requirements as set out by the various standards.

Meanwhile, the fire resistance capacity of normal concrete alone is very complicated because not only is concrete a composite material with components having different thermal characteristics, it also has properties that depend on moisture and porosity [7]. Even though, opinions differ on the changes in OPC concrete particularly in the range 100–300 °C, OPC products are generally regarded as good structural materials with respect to fire resistance; that is, the period of time under fire during which concrete continues to perform satisfactorily [8]. In fact, according to Khoury [9] the compressive strength of Portland-based cement paste and concrete can be maintained without significant loss for temperatures up to about 550–600 °C by the judicious choice of materials. It is feared therefore that inclusion of new materials into the normal concrete might alter the current situations.

Furthermore, most research data related to residual strength after exposure to high temperatures were obtained under conditions of natural cooling which obviously differ from cooling regimes in a real fire. Water-spray is normally applied instead [10]. Therefore, residual mechanical properties reported in most previous literature might be overestimated [11]. In addition, while elucidating the significance of physical properties of concrete exposed to high temperatures, Li et al. [7] pointed out that combining changes in rules of strength, colour and temperature during fire, the retained compressive strength can be inferred primarily.

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It is therefore mainly for these reasons that the present investigation seeks to explore the performance capacity of POFA concrete in response to elevated temperatures. An evaluation of the impact of abrupt cooling caused by water-spray in relation to ordinary air-cooling was also included. In fact, proper understanding of these parameters is much needed towards ensuring that POFA concrete can perform well when exposed to high temperatures especially during accidents such as could occur in fire outbreaks and nuclear reactor pressure vessels.

2. Materials and methods

2.1. Materials

The materials used in the present study include; OPC conforming to BS 12: 1989 [12], POFA with Blaine fineness 519 m^2/kg, dry mining sand with fineness modulus 2.40 and crushed granite with nominal maximum size 10 mm. The POFA was collected from a Malaysian palm oil mill, dried in an oven at 105 ± 5 °C for 24 h, followed by grinding in a modified Los Angeles abrasion machine. The modification entails 10 stainless steels 12 mm ∅ × 800 mm bars instead of the normal steel balls. Previous works [13–15] have found this method to be an effective way of grinding ashes of various kinds. Indeed, the grinded POFA was sieved through 300 μm sieve and the amount passing 45 μm openings was found to be 50%. Chemical composition and physical properties of the OPC and POFA used are shown in Table 1.

2.2. Specimen preparations

Mix design was based on the recommendations by Alves et al. [16]. Table 2 shows the mix proportions as well as 28-days compressive strength for both categories of concretes. Mixing was carried out in a pan mixer conforming to BS 1881-125:1986 [17] and casting was conducted in accordance with BS 1881-108:1983 [18]. Cubes of standard nominal size 100 mm were employed.

After placement, specimens were stored under wet burlap at a temperature of 20 ± 2 °C and 85% RH. All specimens were demoulded after 24 h, and then immersed in water under similar conditions of temperature and relative humidity. At the age of 28 days, cubes were removed from water and allowed to dry in the normal laboratory environment for 24 h.

2.3. Testing program

Prior to testing, all specimens were weighed and the surrounding temperature was noted. While control specimens were tested without any heating treatment, other consignments were then heated to the required temperature levels. However, in order to minimize temperature gradient of the core in relation to the outer surfaces, target temperatures were maintained for 1 h in each case. This action is also believed to contribute towards attaining real situations since it serves as emulation to longer periods of fire ratings.

An electrically controlled furnace was used and the heating rate was 10 °C/min. The temperature–time curve, Curve 2 (C-2) is shown in Fig. 1, which is accompanied by Curve 1 (C-1) and Curve 3 (C-3) from the research conducted by Li et al. [7]. C-1 is the temperature–time curve of Chinese standard GB/T 9978-1999 [19] and C-3 is a temperature–time curve of oil burning furnace achieved by Li et al. [7].

At the end of the heating process, a quick assessment of weights was conducted so as to account for mass loss. While specimens for air-cooling were placed in an open air thereby allowing for a gradual cooling to room temperature, specimens for water-cooling were however subjected to water-spray from a flexible rubber hose until no steam was emitted. Eventually, both categories of specimens were allowed to remain under the same condition of temperature and relative humidity (20 ± 2 °C and 85% RH) for 24 h.

3. Test results and discussions

3.1. Temperature gradient and impact of heating rate

The issue of heating pattern to resemble that of the actual situation is of great importance, so that judgments on laboratory findings can be passed over full scale works with greater precision [7]. However, even though fire outbreaks are often swift in burning actions, especially in incidences involving fuel or highly combustible items, there are instances where the rate of heating generated by fire outbreak may be considered as low; such as the case in poor combustible materials and non ventilated enclosures. These two parallel heating patterns are equally represented by the heating rates involved in C-1 and C-3 on one side and C-2 on the other. Thus, what matters most could be an understanding of the differences in residual characteristics which may occur due to variations in the heating rates, so that while assessing damages caused by fire hazards, appropriate references can be made to suit background nature of the incidence.

In fact, differences in ratings are bound to create differences in thermal degradations and this has been observed by Khoury [9], where the author reported a lower residual strength associated with 0.2 °C/min, contrary to a faster rate of 1 °C/min which resulted in a higher residual strength. Therefore, the temperature gradient between external surface and the core of the specimen under fire will entertain larger differences in relation to a higher heating rate than possibly a minute variation that may occur in slower heating rate. Thus, the slower heating rate allows for more thermal degradations across the specimen through a higher prolonged core temperature. This is also the view held by Khoury [9] in which the slow rate was described as an avenue for more detrimental transformations. However, the possibilities of entrapping more moisture with eventual explosive cracks are more in higher heating rates than in the lower rates.

3.2. Residual compressive strength

Figs. 2 and 3 present residual compressive strength of OPC and POFA concretes respectively. These results show the impact of air and water cooling at various levels of temperatures. However, details on differences based on cooling system were given in the subsequent section. Except in the air-cooling of POFA concrete, there was a continuous decrease in the residual compressive strength with increase in temperature.

The increase in residual compressive strength of POFA concrete between 100 °C and 500 °C via air-cooling could be related to a number of factors; existence of change in thermal strain, fineness of POFA used in the mix and the hydration of unhydrated cement. Rapid change in size due to thermal fluctuations might cause differential thermal strain (DTS) among compositional constituents or two adjacent regions exposed to different temperature levels. Increase in the fineness of POFA improves its reactivity through additional surface area, and it has been noted that the grinding

Table 2
Mix proportions of concrete and 28 days cube's strength.

Constituent (kg/m^3)	OPC	POFA	Constituent	OPC	POFA
Cement	414	440	Water (kg/m^3)	207	154
POFA	–	110	Superplasticiser (L/m^3)	–	5.5
Fine aggregate	619	639	Cube-strength (N/mm^2) at 28 days	44.5	41.0
Coarse aggregate	1139	1139			

Table 1
Chemical composition and physical properties of cementitious materials.

Chemical composition (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI	Surface area (m^2/kg)
OPC	20.2	5.7	3.0	62.5	2.6	1.5	0.16	0.87	1.0	314
POFA	43.6	11.4	4.7	8.4	4.8	2.8	0.39	3.5	9.17	519