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Performance evaluation of concrete containing high volume palm oil fuel ash exposed to elevated temperature

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HIGHLIGHTS

- Concrete containing high volume palm oil fuel ash was thermally treated to elevated temperature.
- The structural behaviour in terms of residual pulse velocity, weight and strength were studied.
- The satisfactory performance of concrete containing ash against high temperature is highlighted.

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ABSTRACT

The properties of concrete exposed to elevated temperature are of great importance in terms of structural stability and assessment of serviceability state of the structure. This paper presents the results of a study on the performance behaviour of concrete containing high volume palm oil fuel ash exposed to high temperature. Concrete samples were made where ordinary Portland cement was replaced by 50%, 60% and 70% palm oil fuel ash. The samples were thermally treated to elevated temperatures of 200, 400, 600 and 800 °C in an electric furnace for a period of 1 h after attaining the peak temperature. Specimens exposed to elevated temperature were cured in air and were tested for visual observation, change in weight, ultrasonic pulse velocity and residual compressive strength. It has been observed that higher the temperature, higher was the residual weight loss of concrete samples. Along with the loss of residual compressive strength, the ultrasonic pulse velocity of concrete was also reduced at elevated temperature. Data generated in this study was used to develop simple relationship for expressing residual compressive strength as a function of ultrasonic pulse velocity.

1. Introduction

With the increasing building activities, more interests have been given in studying the behaviour of concrete at a high temperature mainly resulting from fire. During a fire, the temperature may reach up to 1350 °C in tunnel, reactor vessel, nuclear plant and building under extreme events like blast or impact loading. However, in some special cases, even much lower temperature may cause explosive destruction of concrete, thus endangering the bearing capacity of concrete element. Nevertheless, concrete is considered a construction material that satisfactorily preserves its properties at high temperature. Owing to its fairly low coefficient of thermal conductivity, the movement of heat through concrete is slow. When concrete is heated under conditions of fire, the increase in temperature in the deeper layers of the material is progressive; but because of the slow process, significant temperature gradients are produced between the concrete surface and core inducing additional damage to the element [1–8].

Fundamental issues related to the impact of high temperature on concrete involve identification of the complex changes that take place in concrete while heated. At structural level, the behaviour of the material is characterised by spalling with most cracks parallel to the heated surface. Characteristics such as colour, surface texture, density, volume, compressive strength and elastic modulus are affected remarkably upon heating resulting in a decrease in structural stability of the concrete [9]. Further to that, at elevated temperature the chemical composition and physical properties of the concrete change significantly [4] where dehydration of water from calcium silicate hydrate becomes critical above 110 °C. Over the years extensive research works have been carried out to study the behaviour of concrete at high temperature. Type of concrete materials, moisture condition and the extent of fire has been shown to largely affect the severity of damage to the structure. Although leaner mixes appear to suffer a relatively lower loss of strength than the rich ones, it has been possible to improve fire

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resistance of concrete by the replacement of cement with pozzolanic materials [10–12].

There is no doubt that the last two decades have been characterised by the development of new or largely innovative cementitious composite materials that provide excellent mechanical properties and high durability. These materials, either naturally occurring or artificially made are used throughout the world for their technical, ecological and economic advantages. One of the latest additions to the ash family is palm oil fuel ash (POFA) obtained on burning palm oil husk and palm kernel shell as fuel in palm oil mills. These mills are self-sufficient in terms of energy consumption as the waste materials are used as fuel to run the mill boilers. The ash which was simply thrown away without any commercial return is now considered a useful material showing high performance in the development of strength and durability of concrete at both indoor and outdoor exposure conditions [13–16]. The countries in the equatorial belt that cultivate oil palm are Benin Republic, Colombia, Ecuador, Nigeria, Zaire, Malaysia, Indonesia and Thailand of which Malaysia is the largest producer of palm oil and palm oil products. It has been estimated that the total solid waste generated by this industry in some two hundred palm oil mills in the country has amounted to about ten million tons a year [17,18]. With the expansion of palm oil plantation in South-East Asian regions, the production of palm oil and the consequent ash generation in the mills are expected to increase further.

Advances in concrete technology have led to the application of high volume fly ash to replace OPC in concrete, which has been in practice since last decades. The high volume utilization not only reduces the amount of solid waste and greenhouse gas emissions associated with Portland cement manufacture but also conserves the prevailing natural resources. Strictly, there is no limit for high volume fly ash in concrete, but in general, it refers to structural concrete with fly ash content substantially higher than that used in conventional fly ash concrete, mostly 50% and above of the weight of the binder [19,20]. This practice has been reported to be successful in making both normal and high strength concrete and has influenced various properties of concrete from fresh to hardened state without compromising strength and durability requirements [19–21]. Considering the availability and the potential pozzolanic behaviour of the ash, extensive research work on the utilization of high volume palm oil fuel ash in concrete has been carried out [22,23] in the Department of Structure and Materials, Faculty of Civil Engineering of the University of Technology Malaysia. In order to extend the concept of high volume POFA utilization and to evaluate the effect of exposure to extreme environmental loading like fire, this paper presents the behaviour of palm oil fuel ash concrete exposed to high temperature.

2. Materials and test methods

2.1. Materials

Palm oil fuel ash used in this study was obtained from a palm oil mill located in the state of Johor, Malaysia. The ash was air dried and sieved using BS standard sieves to remove larger particles as well as to reduce the carbon content. Materials passing through 150 μm sieve were ground using a modified Los Angeles milling machine having 10 stainless steel bars of 12 mm diameter × 800 mm length for 2 h per 4 kg of ash. The physical properties and chemical composition of the POFA together with that of ordinary Portland cement (OPC) are presented in Table 2; the scanning electron micrograph (SEM) of POFA being shown in Fig. 3.

A saturated surface dry river sand with fineness modulus of 2.9, passing through sieve size of 4.75 mm having 2.6 specific gravity and water absorption of 0.70% was used as fine aggregate. While coarse aggregate used was crushed granite of 10 mm maximum size with specific gravity of 2.7 and water absorption of 0.5%. RHEOBUILD 1100 (HG), a polymer based superplasticizer was used in order to improve workability and strength of concrete.

2.2. Manufacture of concrete

Table 1 summarizes the mixture proportion, workability and strength of concrete. Ordinary Portland cement was replaced by POFA at replacement levels of 50%, 60% and 70% by weight. Mixing of concrete was carried out using concrete mixer, and workability using slump measurement was done for each mixed batch. Fresh concrete was cast into cube moulds having standard nominal size of 100 mm to obtain test specimen. After casting, the specimens were covered with plastic sheet, demoulded after 24 h and were cured in water at a temperature of 23 ± 2 °C with ±85% RH until testing.

2.3. Time–temperature history of furnace

Prior to testing, all specimens were weighed, and the control specimen was tested for compressive strength without any heat treatment at room temperature of 27 °C. Other samples were subjected to heat treatment in an electric furnace to progressive temperature rise of 200, 400, 600 and 800 °C for a period of 1 h, after attaining the peak temperature. The electrically controlled furnace and its time–temperature curve are illustrated in Figs. 1(a) and 1(b), respectively. The thermally treated specimens were air-cured in the laboratory before they were tested for residual ultrasonic pulse velocity, residual weight and residual compressive strength.

The temperature rating of the furnace known as experimental temperature during testing is shown in Fig. 1(b). Although the heat development was somewhat lower in the furnace, the temperature curve demonstrated comparable behaviour to those of ISO 834 [24] and ASTM E119 [25]. Previous studies by Khaliq and Kodur [2], Chan et al. [26] and Peng et al. [27] showed a similar heating pattern.

2.4. Ultrasonic pulse velocity test

A non-destructive test using ultrasonic pulse velocity (UPV) was conducted with the aid of Proceq apparatus and associated transducer as shown in Fig. 2. The test was conducted after the application of heat to obtain residual UPV. The transducer pair

Table 1
Mix proportion and strength of concrete.

Materials	OPC concrete	50% POFA concrete	60% POFA concrete	70% POFA concrete
OPC (kg/m^3)	380	190	152	114
POFA (kg/m^3)	–	190	228	266
Coarse aggregate (kg/m^3)	1024	1024	1024	1024
Fine aggregate (kg/m^3)	741	741	741	741
Water (kg/m^3)	171	171	171	171
Superplasticizer (l/m^3)	7.6	7.6	7.6	7.6
Slump (mm)	160	130	90	70
28-day compressive strength (N/mm^2)	44.4	35.7	29.5	27.0