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Properties of eco-friendly self-compacting concrete containing modified treated palm oil fuel ash

Belal Alsubari [a], Payam Shafigh [b,d,*], Zainah Ibrahim [c], Mohammed Fouad Alnahhal [c], Mohd Zamin Jumaat [c]

[a] Department of Civil Engineering, Faculty of Engineering, Al-Madinah International University, 40100 Shah Alam, Selangor, Malaysia
[b] Department of Building Survey, Faculty of Built Environment, University of Malaya, 50603 Kuala Lumpur, Malaysia
[c] Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[d] Center for Building, Construction & Tropical Architecture (BuCTA), Faculty of Built Environment, University of Malaya, 50603 Kuala Lumpur, Malaysia

HIGHLIGHTS

- Modified treated palm oil fuel ash (MT-POFA) was used in self-compacting concrete.
- SCC containing MT-POFA has high strength at later ages higher than 60 MPa.
- The use of high volume MT-POFA in SCC improved the properties of the concrete.
- SCC containing high volume MT-POFA is eco-friendly concrete.

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ABSTRACT

Palm oil fuel ash (POFA) is an agro-waste byproduct disposed as landfills without being recycled. Ground POFA is a suitable supplementary cementitious material that can be utilized in different types of concrete. However, problems associated with the reduction of workability and early-age compressive strength of concrete, as well as limited replacement levels of POFA, have been encountered. Heat treatment of ground POFA (T-POFA) can effectively enhance the performance of POFA and reduce its limitations. However, the energy consumed during such heat treatment is high. Moreover, limited original POFA (approximately 30%) can be used to prepare T-POFA. In this study, a new method was introduced to prepare treated POFA, called modified treated POFA (MT-POFA) with full usage of original POFA. MT-POFA was then used as a cement replacement at 0%, 30%, 50%, and 70% to produce sustainable self-compacting concrete. Test results showed that the fresh properties of all concretes containing MT-POFA were ranged within SCC requirements. The mechanical properties exhibited a reduction in the early ages of MT-POFA concretes; however, with increased curing time, these properties were significantly improved. SCC incorporating MT-POFA exhibited significant resistance against rapid chloride permeability test and elevated temperature, and performed better than the control SCC. In general, MT-POFA exhibited significant potential use as a cement replacement in self-compacting concrete.

1. Introduction

Cement production is very energy intensive, and optimizing energy consumption is essential. Currently, the global consumption of cement is approximately 3.3 billion tonnes annually, and is increasing at almost 1% per year [1,2]. Cement production involves approximately 110 kWh/t of electrical energy [2]. Approximately 60% of the total energy used in cement manufacturing was reported to be consumed during raw grinding approximately 25% and finishing grinding by approximately 40%, whereas, the remaining 35% is consumed during clinker burning (20%) and auxiliary (15%) steps [3]. Therefore, decreasing energy use and energy-related environmental emissions are crucial.

With the increasing pressure on the construction industry to reduce and optimize energy and cement consumption, the use of supplementary cementitious materials (SCMs) is a possible

Abbreviations: POFA, palm oil fuel ash; U-POFA, ungrounded palm oil fuel ash; G-POFA, ground palm oil fuel ash; T-POFA, treated palm oil fuel ash; MT-POFA, modified treated palm oil fuel ash.

* Corresponding author at: Department of Building Survey, Faculty of Built Environment, University of Malaya, 50603 Kuala Lumpur, Malaysia. Tel.: +60172437383; fax: +60379675713.

E-mail addresses: belalalsubari@gmail.com (B. Alsubari), pshafigh@gmail.com (P. Shafigh).

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solution to reduce the global CO_2 emissions due to cement production [4–6]. To reduce approximately 1 billion tonnes of CO_2 per year through the concrete sector, approximately 50% of the cement clinker must be substituted with materials produced with very low CO_2 emissions. This would require 1.7 billion tonnes of alternative SCM annually [7]. Although fly ash was successfully utilized in concrete production, the quantity used is still lower than the targeted amount to achieve the required CO_2 reduction. Hence, other SCMs should be increasingly brought into the concrete mixture.

Palm oil fuel ash (POFA) is an agro-waste byproduct material and is recognized as a SCM to be utilized in concrete to improve its properties. U-POFA is milled to be a suitable cement replacement and is utilized to produce normal [8], high-strength [9], and self-compacting concrete (SCC) [10]. However, problems associated with the reduction of workability and early-age compressive strength as well as its limited replacement usage in concrete has been encountered. Recently, ground POFA (G-POFA) was heat treated and utilized to produce high-strength and self-compacting concrete [11,12]. Concretes containing T-POFA showed better performance compared with the concrete with G-POFA due to the loss on ignition (LOI) reduction and chemical composition improvement. However, T-POFA possesses some drawbacks, such as having a lengthy process for preparation and high energy consumption during production. In addition, only approximately 30% of the original POFA collected from palm oil mill is used for the final product. This phenomenon is because the original POFA should be passed through sieves with small sizes to separate big particles, and the remaining POFA is thrown again as waste [13].

Hence, a new method was developed to optimize the energy consumption, reduce the time, and utilize the total amount of the original POFA without sieving to produce modified treated POFA (MT-POFA). In this study, moderate- and high-volume MT-POFA were utilized to produce low-cost SCC with a minimal effect on the environment. The fresh properties of SCCs were assessed to study SCC requirements. In addition, hardened properties, such as compressive strength, modulus of elasticity (MOE), splitting tensile strength, water absorption, rapid chloride permeability, and fire resistance tests, were studied.

2. Materials and testing methods

2.1. Binder

Ordinary Portland cement (OPC) and MT-POFA were used as binders. The original POFA was collected from a palm oil mill located in Selangor state, Malaysia. Then, it was placed in an electrical furnace at 600 °C for 2 h without sieving. After that, it was subjected for grinding using a Los Angeles abrasion machine to reduce the particle size and increase the surface area. A total of 30 mild steel bars with diameters of 10 mm and lengths of 500 mm were placed in the rotating cylinder, together with 6 kg of the burned POFA. To grind the burned POFA, the machine was timed to run for 18 h using an electric motor at a speed of 33 rpm.

Fig. 1 shows the steps of preparing of T-POFA and MT-POFA. As shown in this figure, two steps, namely, drying and sieving of original POFA, were eliminated for MT-POFA and time was consequently lesser compared with the previous method [11,12,14].

To ensure the efficiency of the MT-POFA, physical and chemical composition tests were evaluated. The particle size distribution, specific surface area, and median particle size were measured using a particle size analyzer. X-ray fluorescence used to determine the elemental composition of POFA before and after heat treatment. A field emission scanning electron microscope (FESEM) was also utilized to assess the changes in the morphology of the POFA due to the heat treatment. Also, X-ray diffraction (XRD) is an analytical technique used to identify the major phases in the U-POFA, G-POFA, T-POFA, and MT-POFA. In order to ensure the efficiency of MT-POFA, its physical and chemical composition results were compared with the results for T-POFA reported from previous study [11,12].

2.2. Aggregate

Local mining sand and crushed granite were used as fine and coarse aggregates, respectively. Some properties of aggregates are presented in Table 1.

2.3. Concrete mix proportions and mixing procedure

A total of four different SCC mixes were produced with 0%, 30%, 50%, and 70% MT-POFA substitution (by weight) of the total binder. Table 2 shows the proportions of all SCCs mixes. The binder content and water/binder ratio were 480 kg/m^3 and 0.35, respectively. An appropriate control mix that fulfilled the requirements of fresh properties of SCC was chosen from different trial SCC mixes.

For the mixing of the constituent materials, the coarse and fine aggregates were mixed for 1 min. Approximately 10% of mixing water was initially added and mixed for 5 min. The cement and MT-POFA were later added to the mix. The remaining water together with superplasticizer was added to the mix and the mixing was continued for 7 min.

3. Testing methods

3.1. Fresh properties

The fresh properties, such as filling ability, passing ability, and segregation resistant, were assessed for all concretes according to European Federation of National Associations Representing for Concrete [15]. Filling ability was checked with respect to slump flow, $T_{50\ cm}$, and V-funnel. The slump flow test was conducted to evaluate the ability of fresh concrete to flow horizontally without objections, and $T_{50\ cm}$ was recorded at the same time.

The passing ability of fresh concrete was checked to ensure that the concrete can pass through congested reinforcement and small openings without any vibration. The J-ring flow test was used to assess the passing ability of fresh concrete. Segregation resistance of the fresh mix was evaluated with respect to GTM screen stability test method to ensure that concrete remains cohesive and stable during casting.

3.2. Compressive strength under standard and non-standard curings

Three cubes of 100 mm were used to determine the compressive strength of SCCs at 1, 7, 28, 56, and 90 days. To evaluate the effect of different curing methods on the compressive strength of concrete, samples were cured inside (indoor) and outside (outdoor) the laboratory. Then, four types of curing regimes were used, namely, continuous water curing, air drying, initial water curing for 7 days followed by air drying, as well as plastic wrapping up to 28 days. A 3000-kN-capacity compression-testing machine was used to test cube specimens, as per BS EN 12390-3:2002 [16].

3.3. Splitting tensile test

The splitting tensile strength test was conducted on a cylinder having a diameter of 100 mm and a height of 200 mm, according to ASTM C 496/C 496M [17]. The specimens were tested on the ages of 28th and 56th day of water curing. In this test, the specimen was positioned at the center with packing strips placed along the top and bottom diametrical faces. Thin plywood bearing strips