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Development of green ultra-high performance fiber reinforced concrete containing ultrafine palm oil fuel ash

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HIGHLIGHTS

- We develop a new class of green UHPFRCCs, designated as (GUSMRC).
- We examine the changes in the UPOFA content about properties of GUSMRC mixtures.
- We optimize the binder content of GUSMRC mixtures using RSM.

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ABSTRACT

This paper presents an ideal experimental design based on the response surface method (RSM) to develop a new class of Green Ultra-High Performance Fiber Reinforced Cementitious Composites (GUHPFRCCs), in which 50% of the volume contains ultrafine palm oil fuel ash (UPOFA). This green concrete is currently under development at the Universiti Sains Malaysia (GUSMRC). This could lead to the greater utilization of POFA in concrete and, subsequently, could be useful in protecting the environment by minimizing volume of waste disposed on the wasteland and minimizing emission of greenhouse gases that released during cement production, besides contribute to cost saving which could somehow contribute towards the sustainability of the concrete industry. The results showed that at 90 days the optimum mix was achieved 158.28 MPa, 46.69 MPa and 13.78 MPa of compressive strength, bending tensile strength and direct tensile strength, respectively, with 50% replacement levels of the total binder content by UPOFA, indicating the ability of using UPOFA as an efficient pozzolanic mineral admixture for the production of GUSMRC with promisingly superior engineering properties.

1. Introduction

There is no clear definition of ultra-high performance fiber reinforced concrete (UHPFRC). Fardis [1] defined UHPFRC as a type of concrete structure with a compressive strength of up to 120 MPa as well as high advanced strength, durability, and excellent performance characteristics. This is achieved by optimizing the packing density for all granular raw materials. It can excess more than 150 MPa [2,3], depending upon the concrete whether contain coarse aggregate or steel fiber.

Although no standard has been adopted yet for developing UHPFRC, it has become popular in practical applications [1]. This is due to its advantages in comparison with normal concrete (NC) and high performance concrete (HPC) [4]. The high strength of UHPFRC significantly reduces the member section size and weight [1,5]. Moreover, it enhances the resistivity to aggressive environments and permeability [1,4,6,7].

When compared with NC, the UHPFRC mix is up to three times more expensive [1], owing to the high cement, silica fume, special steel fiber, special aggregates, and chemical admixtures content [1–3,8,9]. This is automatically reflected in the increase of cement production. An increase in the cement content similarly reflects an increase in the cement production [10,11]. However, the increase in cement production leads to an increase in electrical energy consumption [10,11] as well as an increase in greenhouse gases emission, which affects global warming due to gases like carbon dioxide (CO_2) [1,10,11], sulfur dioxide (SO_2) [12], and nitrogen dioxide (NO_2) [12].

There are several ways to engineer concrete to find a reasonable solution to these problems. One way is by optimizing the mix proportions using mathematical or statistical methods. For example, De Larrard and Sedran [13] optimized the UHPC proportions using a statistical method by packing model.

There is a need to reduce the cement and the silica fume content despite the significant potentials of mathematical and statisti-

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cal methods. The most sensible solution is by replacing greater portions of the cement and silica fume in UHPFRC with manufacturing wastes or by-products as supplementary cementitious materials while maintaining its mechanical properties in general. One of the supplementary cementitious materials used is Palm oil fuel ash (POFA), which has significant potential as a partial cement replacement in concrete [14].

POFA is a by-product from the burning of fruit bunches, shells, kernels, and fibers to be used in generating electricity for the boiler of palm oil mills [15,16]. High amounts of POFA are produced in Malaysia, Thailand, and Indonesia, which are expected to increase annually [14]. Most of the raw materials of POFA are disposed of as waste in landfills, which may contribute to environmental problems in the future [17]. Therefore, much research had been conducted to find a suitable solution in disposing POFA properly.

Many researchers have found that POFA carries pozzolanic qualities and properties. In fact, it can be considered as pozzolanic material [18–20]. POFA has been utilized in many fields, especially in civil and environmental fields. POFA was observed to enhance the transport properties of concrete. It reduces heat development [17] and improves the concrete resistance to chloride ion penetration [20–22], acidic environment [21], and sulfate attack [16]. It also enhances engineering properties such as the flexural performance of engineered cementitious composites (ECC) [14], improving the compressive performance of NC [23,24]. Furthermore, POFA has been utilized in the production of HPC. Therefore, the highest compressive strength was found in the range 60–86 MPa, which was obtained at POFA (median particle size of approximately 10 μm) replacement level of 20% at 28 days with a total binder 550–560 kg/m^3 [25–27].

Recently, Megat Johari et al. [20] modified the treatment and grinding process of POFA production through heat treatment in order to remove the excess carbon content and to decrease the median particle size of POFA by about 2.06 μm. A highly efficient pozzolan was obtained through their treatment processes. The modified ultrafine POFA was utilized for improving the engineering and transport properties of HPC. They found that the compressive strength could exceed 95 MPa after 28 days with a replacement level of up to 60% for producing green HPC containing a high volume of ultrafine POFA. Furthermore, the use of ultrafine POFA, particularly in high volume, could contribute to a healthier and more sustainable environment, increase the green concrete products, and reduce concrete cost.

The literature shows that the utilization of ultrafine POFA in concrete products is still recent, limited, in need of further investigations, e.g., the use of ultrafine POFA in producing the green UHPFRCCs has not been investigated before. The present study investigates the influence of the treated ultrafine POFA on the strength performance and workability of UHPFRCCs.

The main objective of this study is to investigate the potential of ultrafine POFA as a partial binder replacement on the engineering properties of GUSMRCs mixtures.

1.1. Research significance

The present study aims to develop a new class of green UHPFRCCs, containing up to a volume of 50% UPOFA. This green concrete is currently under development at Universiti Sains Malaysia (USM), designated as (GUSMRC). This could lead to the greater utilization of POFA in concrete. Subsequently, it could be useful in protecting the environment by minimizing the volume of waste disposed on the wasteland and minimizing the emission of greenhouse gases. Furthermore, it contributes to cost-saving, which contributes to the sustainability of the concrete industry.

2. Materials and methods

The materials used for producing the controlled mix of UHPFRCCs and the GUSMRC mixes are described in the following subsections.

2.1. Materials

The constituent materials include ordinary Portland cement (American Society for Testing and Materials [ASTM] Type 1, 42.5R); ultrafine POFA with a median particle size of about 2.06 μm, 65.01% silicon dioxide, surface area of 177.50 m^2/kg and specific gravity of 2.55 [20]; densified microsilica fume (DSF) with a particle size of 0.1–1 μm, 92% silicon dioxide, and surface area of 237.000 m^2/kg; mining sand with a particle size of 100 μm to 1180 μm and a specific gravity of 2.65; and two short brass-coated micro-steel fibers (6 and 13 mm) with diameters of 0.16 mm and tensile strength of up to 2850 MPa [28]. The chemical compositions of all the cementitious materials are given in Table 1.

2.2. Mix proportions and samples preparation

The proportions and properties of the controlled UHPFRCC mix were optimized by using the response surface method (RSM) as described in Table 2. These include a total binder (cement & densified silica fume) of 934.74 kg/m^3; mining sand 1057.31 kg/m^3; two short brass-coated micro-steel fibers (6 and 13 mm) with diameters of 0.16 mm and tensile strength of up to 2850 MPa of 390 kg/m^3 and 78 kg/m^3 respectively; and water/binder ratio of 0.18 and a polycarboxylic ether based superplasticizer (PCE-based) dosage of 0.07 by mass of OPC. The compressive strength was up to 181.41 MPa at 28 days and the flow was 167 mm as shown in Table 2.

The same binder content of 934.74 kg/m^3 was used for the GUSMRCs. The UPOFA was utilized as a partial supernumerary of the OPC and DSF on a volume-for-volume basis using the RSM as described in Section 2.3.

2.3. Experimental design and data analysis

The Design-Expert®6.0.7 (Sat-Ease Inc., Minneapolis, USA) software was employed for data analysis and the mathematical and statistical design of the experiments. The RSM and three-level full factorial experimental design were incorporated to provide the optimization by maximizing the strength of GUSMRC at the maximum replacement levels of the OPC and DSF by UPOFA. A preliminary experimental study was initiated for determining the narrower ranges of the replacement levels (%) of the OPC by UPOFA and DSF by UPOFA prior to designing the experimental runs. Accordingly, the reasonable ranges were selected as OPC by UPOFA replacement levels ([OPC-UPOFA]%) from 0.0% to 50% and replacement levels ([DSF-UPOFA]%) from 0.0% to 100%. The other ingredients of the controlled UHPFRC mix remained the same to ensure that any changes in the engineering properties of the GUSMRCs would be due to the partial replacement levels of OPC and DSF by UPOFA.

The most regular design methods used under RSM is the central composite design method (CCD) [29], in order to find the functional relationship between the responses (compressive strength and flow) and the factors ([OPC-UPOFA]% and [DSF-UPOFA]%) using RSM. The total number of experiments for the two factors were 13, obtained as (13 = 2k + 2k + 5), where k is the number of factors (k = 2). Eight experiments were enhanced with five replications to assess the pure error. A total of 13 runs of the CCD experimental design and responses based on the experimental runs are shown in Table 3. The quadratic model was suggested by the program. The optimum predictor quadratic model equation shown below was used to determine the optimum condition of the responses [30,31]:

$$Y = \beta_0 + \sum_{i=1}^{k}\beta_{ii}X_i + \sum_{i=1}^{k}\beta_{ii}X_i^2 + \sum_{i_{i\leq j}}^{k}\sum_{j}^{k}\beta_{ij}X_iX_j + e_i \tag{1}$$

where Y is the predicted response, X_i, and X_j are the coded values of the preparation variables, i is the linear coefficient, j is the quadratic coefficient, β is the regression coefficient, k is the number of factors studied and optimized in the experiment and e is the random error. The coded points, actual points, and their corresponding values are described in Table 3. The mix compositions for the GUSMRCs were determined from the preliminary study, research literature, and statistical RSM (Table 4).

The interaction and relationship between the process factors ([OPC-UPOFA]% and [DSF-UPOFA]%) and the responses (compressive strength and flow) were obtained from the analysis of variance (ANOVA). In order to quantify the quality of the quadratic prediction models, to evaluate the model terms, and to check the model terms statistical significance, the coefficient of determination R^2, the probability (P-value) with 95% confidence level, and (t-test) at 5% significance level (Prob < 0.05) were determined respectively. Moreover, the ramp function graph was used to identify the optimum region.