Materials and Design 54 (2014) 694–701

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Influence of palm oil fuel ash on ultimate flexural and uniaxial tensile strength of green ultra-high performance fiber reinforced cementitious composites

M.A.A. Aldahdooh, N. Muhamad Bunnori *, M.A. Megat Johari

School of Civil Engineering, Universiti Sains Malaysia (USM), Malaysia

ARTICLE INFO

Article history:
Received 29 June 2013
Accepted 27 August 2013
Available online 3 September 2013

Keywords:
Palm oil fuel ash
Efficient pozzolan
Central composite design
Ultimate flexural strength
Ultimate tensile strength

ABSTRACT

This study focuses on the measurement of the ultimate flexural and tensile strength of GUSMRC, a new class of green ultra-high performance fiber reinforced cementitious composites (GUHPFRCCs) in which 75% of the volume contains ultrafine palm oil fuel ash (UPOFA). This green concrete is currently under development at the Universiti Sains Malaysia (GUSMRC). The main objective of this study is to investigate the potential of UPOFA as a partial binder replacement for the ultimate flexural and uniaxial tensile strength of GUSMRC mixtures. Results showed that UPOFA enhances the flexural and uniaxial tensile responses of fresh UHPFRCCs. The highest flexural and uniaxial tensile strength values at the 50% replacement level after 28 days were at 42.38 MPa and 13.35 MPa, respectively, indicating the potential of utilizing UPOFA as an efficient pozzolanic mineral admixture for the production of GUSMRC with superior engineering properties.

1. Introduction

Ultra-high performance fiber reinforced cementitious composites (UHPFRCCs) are novel materials with superior mechanical properties, low permeability [1], and high resistivity to aggressive environments [2,3]. Many UHPFRCCs have been applied recently to different structures and processes such as bridge deck overlays, dam repair, and reinforced concrete beam repair [1,4]. UHPFRCCs are defined as a concrete matrix with a typical strength of 150–200 MPa in compression, 7–15 MPa in uniaxial tension, and 25–40 MPa in bending [5–8]. UHPFRCCs also exhibit high energy absorption capacity [9] and strain hardening under tension [5,10].

UHPFRCC is typically characterized by high contents of cement, silica fume, short steel fibers, special aggregates, and chemical admixtures [5–7], which are automatically reflected in the increase in the cost of UHPFRCC [3], electrical energy consumption [11,12], and greenhouse gas emission [3,11,12]. Several methods have been employed to alleviate the environmental and economic impact of UHPFRCCs. One such method is to engineer concrete with equivalent properties but with less cement or binder. This method can be realized by optimizing the mix design of concrete through mathematical or statistical methods [13,14]. Cement content still requires reduction despite the significant potential of existing mathematical and statistical methods. The most sensible solution is to replace large portions of cement with industrial products such as fly ash [15], silica fume [16], ground granulated blast-furnace slag [17,18], reject fly ash, recycled glass powder [1], and rice husk ash [19] as supplementary cementitious materials.

A new supplementary cementitious material was used recently to address both environmental and economic concerns. The material is palm oil fuel ash (POFA) [20]. POFA is a by-product of the burning of fruit bunches, shells, kernels, and fibers and is utilized to generate electricity for palm oil mill boilers [21]. High amounts of POFA are produced in Malaysia, Thailand, and Indonesia; these amounts are expected to increase annually [20,22]. Many researchers have found that POFA has pozzolanic qualities and properties [23,24]. Ultrafine POFA has been utilized to improve engineering and transport properties that would subsequently enhance the compressive performance of normal concrete (NC) [25], high-performance concrete (HPC) [24], and engineered cementitious composites (ECC) [20].

Literature shows that the recent utilization of ultrafine POFA in concrete products is still limited and requires further investigation. For instance, the use of ultrafine POFA in producing green UHPFRCCs has not been investigated yet.

The main objective of this study is to investigate the potential of UPOFA as a partial binder replacement for the ultimate flexural and uniaxial tensile strength of GUSMRC mixtures.

* Corresponding author. Address: School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300 Penang, Malaysia. Tel.: +60 4 5996259; fax: +60 4 5941009.

E-mail address: cenorazura@eng.usm.my (N. Muhamad Bunnori).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.08.094

1.1. Research significance

This study aims to develop a new class of green UHPFRCCs that contains up to 75% UPOFA. This green concrete is currently being developed at Universiti Sains Malaysia and is designated as GUSMRC. This study may lead to the wider utilization of POFA in concrete and alleviation of both its environmental and economic impact.

2. Materials and methods

The materials utilized to produce the controlled mix of UHPFRCCs and the GUSMRC are described in the subsequent subsections.

2.1. Materials

The constituent materials include ordinary Portland cement (OPC) (American Society for Testing and Materials [ASTM], Type 1, 42.5 R); ultrafine POFA with average particle size of approximately 2.06 μm, 65.01% silicon dioxide, specific gravity of 2.55, and surface area of 177,500 m^2/kg [24,26]; densified micro silica fume (DSF) of a particle size of 0.1–1 μm measured using a laser diffraction particle size analyzer (MASTERSIZER/E), 92% silicon dioxide analyzed by X-ray fluorescence (X-RF) using (X-ray spectrometer, RIX 3000 devise) according to BS EN ISO 12677 [27], and surface area of 237,000 m^2/kg analyzed using Brunauer-Emmett-Teller (BET) method according to BS EN ISO 18757 [28]; mining sand with a particle size of 100–1180 μm, BET surface area of 0.7777 m^2/g, and specific gravity of 2.65 measured using Pycnometer according to BS 812: Part 2 [29]; and two short brass-coated micro-steel fibers (6 mm and 13 mm) with a diameter of 0.16 mm and tensile strength of up to 2850 MPa [30]. A polycarboxylic ether-based superplasticizer (PCE-based) dosage was utilized. The chemical compositions of all the cementitious materials are provided in Table 1.

2.2. Mix proportions and design

The complete details regarding the mix proportions based on RSM are listed in Table 2. Where, the controlled mix proportions were optimized using RSM in the previous research [31].

2.3. Experimental design and data analysis

Design-Expert® 6.0.7 (Sat-Ease Inc., Minneapolis, USA) was employed for data analysis as well as for the mathematical and statistical design of the experiments. Response surface method (RSM) and three-level full factorial experimental design were incorporated to determine optimization by maximizing the strength of GUSMRC at the maximum replacement levels in which OPC and DSF can be replaced with UPOFA. The most commonly utilized design method in RSM is central composite design (CCD) [32], which was employed in the present study to determine the functional relationship between the responses (ultimate flexural and uniaxial tensile strength) and factors ([OPC-UPOFA]% and [DSF-UPOFA]%). A quadratic model was recommended by the program to determine the optimal condition for the responses. The optimal predictor quadratic model equation utilized to determine the optimal condition of the responses is shown below [33].

$$Y = \beta_o + \sum_{i=1}^{k}\beta_{ii}X_i + \sum_{i=1}^{k}\beta_{ii}X_i^2 + \sum_{i_{i<j}}\sum_{j}^{k}\beta_{ij}X_iX_j + e_i \quad (1)$$

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 random error.

The GUSMRC mixes were classified into three groups based on CCD as shown in Table 2. The first group (G (I)) includes mix Nos. 1 to 3. The second (G (II)) and third groups (G (III)) include mix Nos. 4 to 10 and mix Nos. 11 to 13, respectively.

The interaction and relationship between the process factors ([OPC-UPOFA]% and [DSF-UPOFA]%) and responses (ultimate flexural and uniaxial tensile strength) were obtained through analysis of variance (ANOVA). Coefficient of determination R^2, probability (P-value) with 95% confidence level, and t-test at 5% significance level (Prob. < 0.05) were determined to quantify the quality of the quadratic prediction models, evaluate the model terms, and determine the statistical significance of the model terms, respectively. A ramp function graph was utilized to identify the optimum region.

2.4. Specimen preparation

The GUSMRC mixing and casting procedures recommended by Benson and Karihaloo [16] were adopted to mix the conventional UHPFRCCs.

2.5. Test methods

A pan mixer was employed to mix the GUSMRC, and a vibration table was utilized to compress the samples after casting. The samples were de-molded after 24 h. The recommended curing regime for conventional UHPFRCCs was performed, including steaming at 90 °C and 100% relative humidity for 48 h [2,34]. Lastly, the samples were cured in water with a temperature of 27 °C ± 2 °C until the testing day.

2.5.1. Four-point bending test

Four-point bending tests were conducted for bending tensile strength (flexural strength) measurement. The beams utilized to measure bending tensile strength had a length of 279 mm, cross section of 51 mm × 51 mm, upper loading span of 76 mm, lower support span length of 229 mm according to ASTM: C1018-97, and cross-head loading rate of 0.1 mm/min [35]. The tests were performed with 100 kN AG-X Shimadzu Universal Testing Machine. At least three samples of each mix were tested at each age at the 7th and 28th day.

2.5.2. Uniaxial tensile test

Dog bone-shaped specimens with tested section lengths of 80 mm and cross sections of 16 mm × 30 mm were utilized to

Table 1
Chemical composition of ordinary portland cement, densified silica fume and ultrafine POFA (%).

Compositions	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	P_2O_5	K_2O	SO_3	TiO_2	MnO	Na_2O	C	LOI
OPC	19.01	4.68	3.2	66.89	0.81	0.08	1.17	3.66	0.22	0.19	0.09	–	2.48
DSF	92.26	0.89	1.97	0.49	0.96	–	1.31	0.33	–	–	0.42	0.09	4.96
UPOFA [24]	65.01	5.72	4.41	8.19	4.58	4.69	6.48	0.33	0.25	0.11	0.07	0.09	2.53

OPC = Ordinary Portland Cement, DSF = Densified Silica Fume and UPOFA = Ultrafine Palm Oil Ash [24].