Construction and Building Materials 64 (2014) 253–260

Contents lists available at ScienceDirect

Construction and Building Materials

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

Flow characteristics of ternary blended self-consolidating cement mortars incorporating palm oil fuel ash and pulverised burnt clay

Ibrahim Ogiri Hassan [a], Mohammad Ismail [a,*], Parham Forouzani [a], Zaiton Abdul Majid [b], Jahangir Mirza [c]

[a] UTM Construction Research Centre, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b] Faculty of Science, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[c] Research Institute of Hydro-Quebec, 1840 Lionel Boulet, Varennes, Quebec J3X 1S1, Canada

HIGHLIGHTS

- Flow characteristics of ternary blended self-consolidating mortar.
- Self-consolidating mortar incorporating palm oil fuel ash (POFA) and pulverised burnt clay (PBC).
- Effect of high range water reducer (HRWR) on the blend of POFA and PBC.
- Flow ability of the various mortars with different mix proportion.
- Addition of a blended POFA and PBC prevented the bleeding of the mortars.

ARTICLE INFO

Article history:
Received 4 July 2013
Received in revised form 31 March 2014
Accepted 4 April 2014
Available online 4 May 2014

Keywords:
Flow characteristics
Self-consolidating mortar
Palm oil fuel ash
Pulverised burnt clay
Relative flow area

ABSTRACT

This article aims at investigating the flow characteristics of self-consolidating cement mortars incorporating palm oil fuel ash (POFA) and pulverised burnt clay (PBC). These mortars were tested with respect to their flow spread. Fifteen (15) different cement mortar mixtures were prepared containing Ordinary Portland Cement (OPC) and a blend of POFA and PBC at 0%/0%, 5%/5%, 10%/5%, 10%/10% and 15%/15% as a replacement of OPC. Water-to-binder ratio (W/B) of 0.3, 0.35 and 0.4 were used in all the mortar mixtures. The flow spreads of the mortars were determined using a standard flow mould and subsequently the relative flow areas were measured. The effects of different W/B, high range water reducer (HRWR) dosage and the blend percentage of POFA and PBC on flow characteristics of the various mortars were analysed and reported. Results showed that the flow of the mortar increased with the increase in POFA/PBC content and HRWR dosage while it decreased at higher W/B. Nonetheless, higher dosage of HRWR resulted in the bleeding of mortar. This study also showed that blended POFA/PBC can be used up to 30% replacement with a maximum HRWR content of 2.5% to design and produce self-consolidating cement mortar and concrete.

1. Introduction

Self-consolidating concrete (SCC) achieves its compatibility state through consolidation of the constituent materials by the action of natural gravity [1,2]. The chief driver that ensures the attainment of this stable state is the mortar component of the concrete, which occupies about 70% of the total concrete volume. In fact, the rheological properties and flow ability of fresh concrete depend on the characteristics of its mortar component. In effect, optimum mix design of SCC is achieved by adequately proportioning the key constituent materials of the mortar component. Recent studies have advocated that flow ability of self-consolidating mortar is affected by W/B, HRWR dosage and the characteristics of the supplementary cementing materials (SCM). Consequently, understanding the rheological and flow characteristics of self-consolidating cement mortar (SFCM) is the key to the effective design and the characterisation of the resultant concrete [3–5].

Flow is an important workability characteristic of SCC. It enables SCC to reach all the nooks and crannies of formwork. It also passes through congested reinforcement without any compaction or any form of bleeding or segregation under its self-weight [6,7]. The flow characteristic of SFCM is usually obtained by measuring the flow spread of the mortar [7]. Although the flow characteristic of SFCM depends on the water demand of the SCM and the mix proportion, it is greatly influenced by the addition of an

---

* Corresponding author. Tel.: +60 75531757; fax: +60 75566157.
E-mail address: mohammad@utm.my (M. Ismail).

http://dx.doi.org/10.1016/j.conbuildmat.2014.04.057
0950-0618/© 2014 Elsevier Ltd. All rights reserved.

appropriate dosage of HRWR [7]. Previous researches have indicated that the addition of SCM such as fly ash, silica fume, rice husk ash and ground slate, etc., improves the fluidity and stability of SCC. These materials are used either as binary [7,9–11] or ternary [8,9] blends in most of the cases. It is in this regard that this paper focuses on the use of ternary blend incorporating OPC, POFA and PBC to produce SCC.

Palm oil fuel ash (POFA) is generally classified as an agro-industrial waste. It is obtained from the processing of agricultural product, where the generated waste undergoes further processing by burning at a temperature of about 800-1000 °C to generate electricity [12]. In Malaysia alone, about 3 million tons of ash is generated annually. This quantity of ash is usually dumped in landfills or open fields, thus constituting environmental pollution and health hazard problems [13,14].

The clay brick production process mainly consists of excavation from the borrow pit, followed by crushing, screening, grinding, mixing, extruding, moulding, drying and firing. The most important operation that directly affects the suitability of the clay brick for use as pozzolanic material is the firing process. The strength, durability and chemical characteristic of the brick are determined by the properties of the minerals content and temperature at which it is calcined. This temperature normally ranges between 800 and 1100 °C [15,16]. Analysis of clay calcined at 600-800 °C, revealed that crystalline structure of illite still exists. On the other hand, clay calcined above 900 °C shows complete disintegration of illite. Additionally, significant reductions of anhydrite and quartz as well as growth of plagioclase feldspar were observed. At a calcination temperature of 900-1100 °C, pozzolanic activity is primarily derived from amorphous glassy phase. This phase is associated with reduced amount of residual anhydrite, thus, ensuring long term strength development and better durability [17–20].

Brick remained the second most dominant material in the construction of residential houses, accounting for about 25% of the total building materials requirement by mass [21,22]. Bricks are largely classified as waste when broken or damaged from its production line, construction and demolition sites. Brick and concrete usually constitute up to 75% of construction and demolition waste that are, in most cases, dumped on open landfills. Hence, they contribute significantly to the environmental health hazard [23–26].

Review of literature on SCC revealed that limited research has been conducted on the use of POFA or PBC for its production. Report on the available research shows that the addition of POFA in excess of 20% induces segregation and bleeding [27]. On the other hand, the addition of PBC up to 37.5% improves the rheological properties [28]. In view of these complimentary characteristics, blended POFA and PBC could be used to improve the fresh properties of SFCM and the parent SCC. In fact, no published work exists on the application of the blended POFA and PBC to produce SCC. Hence, investigating the effect of blended POFA and PBC on the workability or flow characteristics of SCC is an important prerequisite. But as advocated by past researchers, carrying out flow test on concrete is often very difficult and time-consuming. The difficulty arises from the need to cover a wide range of variables associated with numerous trial mixes having relatively large batch sizes [3,5,7].

In this study, the flow characteristic of various mixes of SFCM incorporating a ternary blend of OPC, POFA and PBC is presented. The effects of HRWR dosage, blended POFA and PBC contents and W/B on the flow spread as well as the relative flow area of mortars are studied. The results of this research would provide useful performance data that will facilitate effective and appropriate mix design of SCC incorporating POFA and PBC. This approach is, therefore, very important because it reduces both the volume and time of laboratory work since it is limited to the mortar component of the concrete.

2. Experimental

2.1. Constituent materials

Ordinary Portland Type I cement, conforming to ASTM C 150 [29] was used in this study. Its specific surface area was 5.067 m^2/g determined by using Brunauer Emmet and Teller (BET) method. POFA and PBC with a specific gravity of 2.42 and 2.69 and BET surface area of 23.751 and 2.979 m^2/g, respectively, were used. A well graded pit sand having a fineness modulus of 2.4, a specific gravity of 2.55, and absorption value of 1.8% was used. The superplasticizer (SP) used is an ASTM C494 [30] class F polycarboxylic-based HRWR. It is amber in colour and has a specific gravity of 1.10 at 25 °C with a pH value of 8. The major chemical and physical properties of the constituent materials are given in Tables 1 and 2, respectively.

2.2. Mortar formulation and nomenclature

The formulated mortars were classified into three groups based on the W/B and in accordance with the parent SCCs. The W/B, POFA and PBC contents were the same as those used in the parent concretes. The same goes for the proportions of cement, POFA, PBC, sand and water in the respective mortar mixes.

The respective mortars nomenclature was based on the W/B and the proportions of the SCM as present in the parent SCCs. For instance, "30M1P0:0" designation was used for mortar prepared with W/B ratio of 0.3, 0% POFA and 0% PBC. The mix proportion and the designation of the various mortars are presented in Table 3.

Table 1
Chemical properties of powders used as binder.

Oxide composition	PBC (%)	POFA (%)	OPC (%)
SiO_2	68.6	63.7	16.4
Al_2O_3	20.6	3.68	4.24
Fe_2O_3	4.66	6.27	3.53
CaO	0.34	5.97	68.3
K_2O	3.99	9.15	0.22
P_2O_5	–	4.26	–
MgO	0.34	4.11	2.39
SO_3	–	1.59	4.39
Cl	–	0.5	–
TiO_2	0.63	0.3	0 < LLD
Na_2O	0.32	0 < LLD	–
Mn	–	0 < LLD	0.15
CO_2	0.1	–	0.1

Table 2
Physical properties of powders used as binder.

Material	Properties
Fine aggregate	Specific gravity on saturated surface dry bases: 2.55 Absorption: 1.8% Total evaporable moisture content: 1.0% Finesse modulus: 2.4 Void content: 33.4%
Ordinary Portland Cement (OPC)	Specific gravity: 3.15 Percentage passing 45-μm wet sieve: 98.6% Specific surface area (BET): 5.067 m^2/g Median particle size: 15 μm
Palm oil fuel ash (POFA)	Specific gravity: 2.42 Percentage passing 45-μm wet sieve: 98.4% Specific surface area (BET): 23.7514 m^2/g Median particle size: 11 μm
Pulverised burnt clay brick (PBC)	Specific gravity: 2.69 Percentage passing 45-μm wet sieve: 96.4% Specific surface area (BET): 2.9791 m^2/g Median particle size: 10 μm
High range water reducer (HRWR)	Specific gravity: 1.10 pH value: 8 Solid content: 42%

Table 3
Nomenclature and mixture proportions of various mortar groups.

Mortar nomenclature	Percentage replacement		W/B	Fine aggregate (kg)	Cement (kg)	POFA (kg)	PBC (kg)	Water (kg)	HRWR dosage (%B)		Group
	POFA (%)	PBC (%)							Sd[a]	Ud[b]	
30M1P0:0	0	0	0.30	4.77	3.14	0.00	0.00	1.02	1.50	1.00–2.50	1
30M2P5:5	5	5	0.30	4.77	2.79	0.15	0.15	1.01	1.75	1.00–2.50	
30M3P10:5	10	5	0.30	4.77	2.61	0.31	0.15	1.00	2.00	1.50–3.00	
30M4P10:10	10	10	0.30	4.77	2.45	0.31	0.31	1.00	2.25	1.50–3.00	
30M5P15:15	15	15	0.30	4.77	2.12	0.45	0.45	0.99	2.50	1.75–3.00	
35M1P0:0	0	0	0.35	4.77	2.90	0.00	0.00	1.10	1.25	1.00–2.50	2
35M2P5:5	5	5	0.35	4.77	2.58	0.14	0.14	1.09	1.50	1.00–2.50	
35M3P10:5	10	5	0.35	4.77	2.42	0.28	0.14	1.08	1.75	1.25–2.50	
35M4P10:10	10	10	0.35	4.77	2.27	0.28	0.28	1.07	2.00	1.50–3.00	
35M5P15:15	15	15	0.35	4.77	1.96	0.42	0.42	1.06	2.25	1.50–3.00	
40M1P0:0	0	0	0.40	4.77	2.70	0.00	0.00	1.16	1.00	1.00–2.50	3
40M2P5:5	5	5	0.40	4.77	2.4	0.13	0.13	1.15	1.25	1.00–2.50	
40M3P10:5	10	5	0.40	4.77	2.25	0.27	0.13	1.14	1.50	1.00–2.50	
40M4P10:10	10	10	0.40	4.77	2.11	0.26	0.26	1.14	1.75	1.00–2.50	
40M5P15:15	15	15	0.40	4.77	1.83	0.39	0.39	1.13	2.00	1.00–2.50	

[a] Saturation dosage of HRWR (this is the optimum dosage required to produce the parent concrete based on the flow test carried out on mortar).
[b] Used dosage of HRWR (this is the range of dosages used in carrying out the flow test so as to obtain the saturation dosage).

2.3. Mixture proportions

In this study, a total of 15 different mortar mixtures were prepared for groups 1-3. They were based on the mixture proportion of the corresponding SCCs. The mortar volumes were calculated based on the requirement of the minimum paste and mortar volumes required for SCC formulation. The total volumes of mortar calculated were scaled down to 4 l as shown in Table 3. The scaling down was carried out so as to minimise a significant loss of material, time and labour. The HRWR was used as an additive and its dosages varied within the vicinity of its saturation.

2.4. Mortar preparation

The mortars were prepared using a medium sized revolving type mechanical mixer conforming to ASTM C 305 [31] specification.

2.5. Mortars testing

The various groups of mortars were tested to evaluate their respective flow characteristic in terms of their flow spread and flow area. The mortar flow spread test is a replica of the concrete slump flow test but on a smaller scale. The slump flow test is generally considered the standard method of determining the flow characteristic of SCC. In short, results of other studies have shown a very good relationship between the flow spread of mortar and the slump flow of concrete [5,32,33].

A standard flow mould as recommended by ASTM C 230/C 230M [34] was used to determine the flow spread of the respective mortars. Subsequently, the relative spread area (Γ) was calculated using the following equation:

$$\Gamma = \left(\frac{SF}{100}\right)^2 - 1$$

where: Γ = relative spread area, SF = the mean slump flow (flow spread) in mm.

The flow mould was placed over a horizontal levelled plexiglas plate. The mortar was poured into the mould in one layer and without any compaction. Subsequently, the mould was lifted vertically so that the mortar can flow freely over the plexiglas plate. The test set up to determine the mortar flow spread is shown in Fig. 1. The diameter of the mortar spread was measured along two pairs of perpendicular lines that divided it into eight equal segments. The average diameter of the flow spread of mortar was recorded and reported.

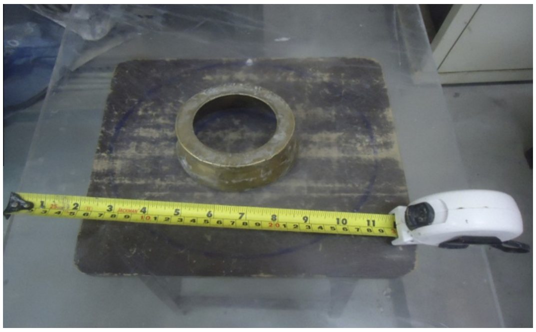

Fig. 1. Test setup for the determination of mortar flow spread.

3. Results and discussion

The results of the mini cone mortar flow test are presented in Figs. 2–7. The figures illustrate the flow characteristics exhibited by the different groups of mortars. The flow characteristics are expressed in terms of the mortar flow spread and the relative flow area at varying dosages of HRWR. The flow spread varied in the range of 235 - 300 mm for the different groups of mortar at incremental dosages of HRWR. On the other hand, the mortar flow spread at saturation dosages of the respective mortars ranged between 275 mm and 300 mm, which are greater than 260 mm as specified by EFNARC [6]. This increase in flow spread is the result of improvement in mortars viscosity and is due to the presence of PBC which was used in the mix as a viscosity modifier. Mortar flow spread of 190 - 300 mm produced SCCs with slump flows of 550 - 850 mm [7]. In addition, the relative flow area of the various mortars ranged between 5.0 and 8.3 (Fig. 5). This range produces stable mortar adequate for the design of SCC. Similar finding was also reported by Yahia et al. [35].

3.1. Effect of mix composition and various parameters

The pattern of the curves presented in Figs. 2–5 is particularly due to the variation in the volume fractions of binder, its surface area, volume fraction of paste and sand-to-binder ratio (S/B). The pattern is not affected by the volume fraction of sand because the sand content is constant for all the groups. These parameters are presented in Table 4.

The flow curves provided in Figs. 2–5 show that mortars that fall within group 1, consisting of 30M1P0:0, 30M2P5:5, 30M3P10:5, 30M4P10:10 and 30M5P15:15 exhibited higher flow spread and relative flow areas at saturation dosages of HRWR in comparison with mortars in groups 2 and 3. The higher flow spread and relative flow area of the group 1 mortars are largely due to the fact that the volume fraction of binder is high, with a lower S/B. These combined effects, reduce the friction at the sand-paste interface, thereby, improving the mortars plasticity and cohesiveness. It also decreases the mortar resistance to flow and increases

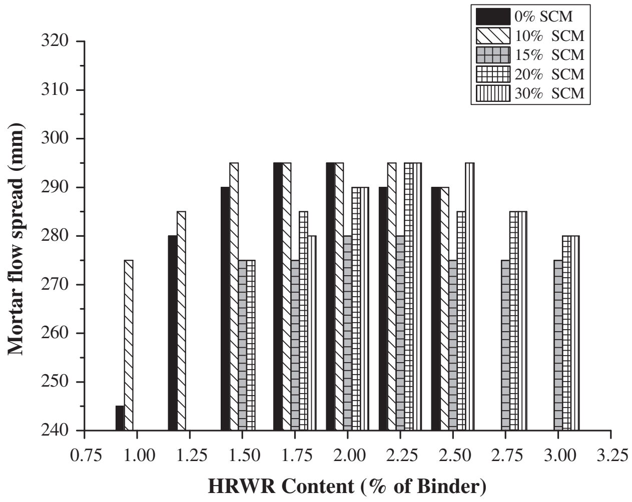

Fig. 2. Flow spread of various mortars in group 1.

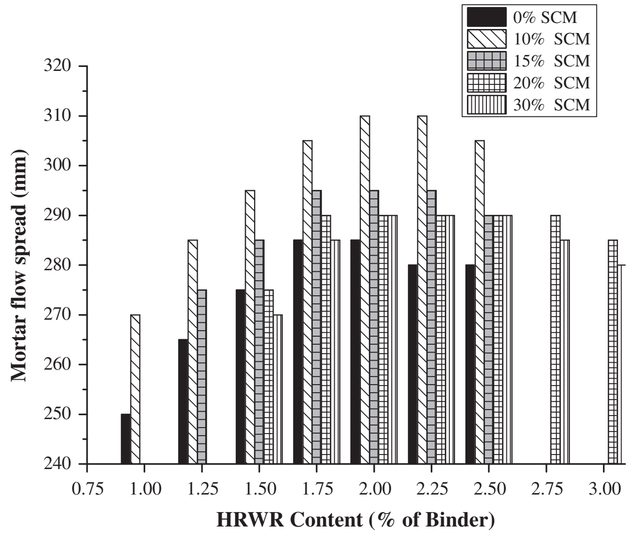

Fig. 3. Flow spread of various mortars in group 2.

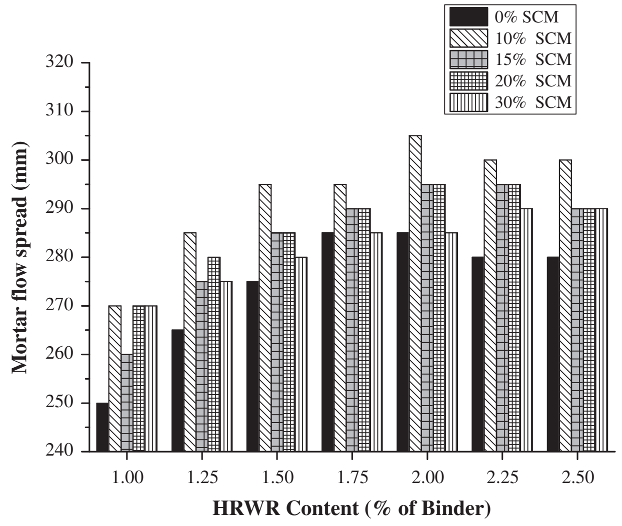

Fig. 4. Flow spread of various mortars in group 3.

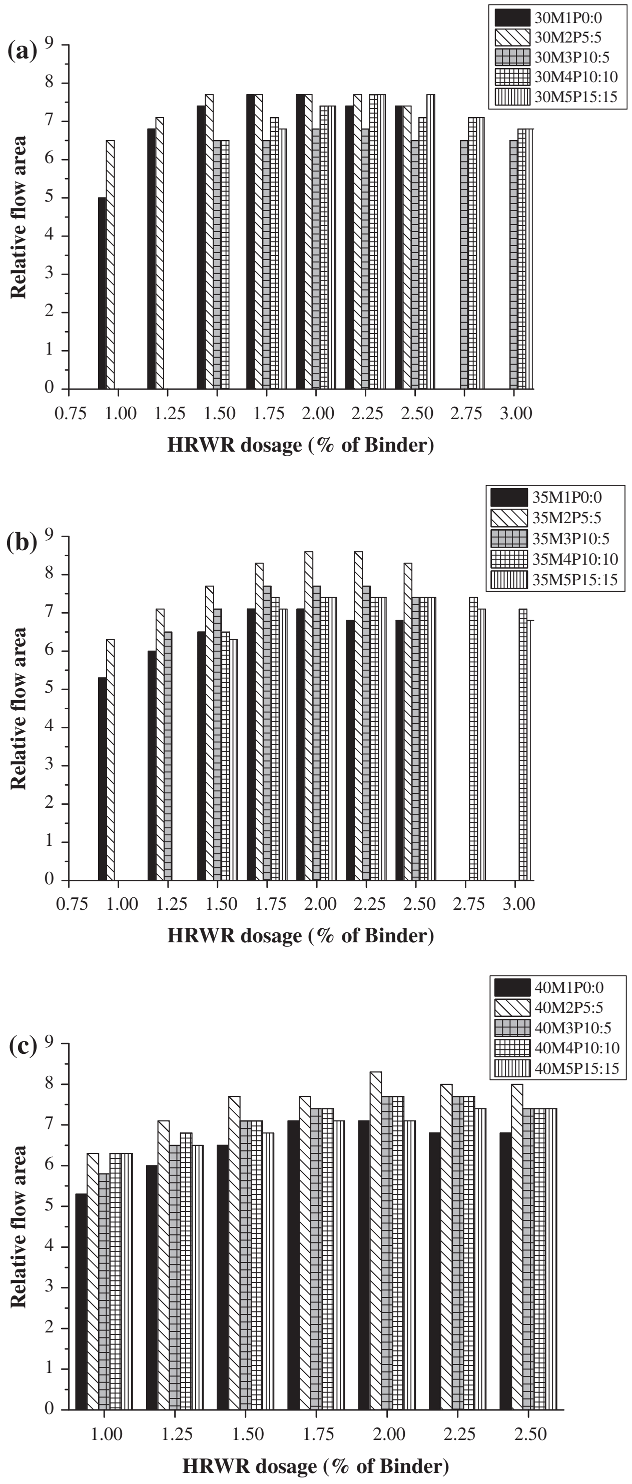

Fig. 5. (a, b, c) Relative flow area of various mortars in groups 1, 2 and 3.

workability [35,36]. On the other hand, group 2 mortars, consisting of 35M1P0:0, 35M2P5:5, 35M3P10:5, 35M4P10:10 and 35M5P15:15 contain lower volume fraction of binder with slightly higher S/B in comparison with group 1 mortars. Conversely, group 3 mortars consisting of 40M1P0:0, 40M2P5:5, 40M3P10:5, 40M4P10:10 and 40M5P15:15 contain lower volume fraction of binder with much higher S/B in comparison to groups 1 and 2 mortars.

It was reported by Okamura and Ozawa [3] that at higher S/B, there is higher amount of water confined by the sand, leading to

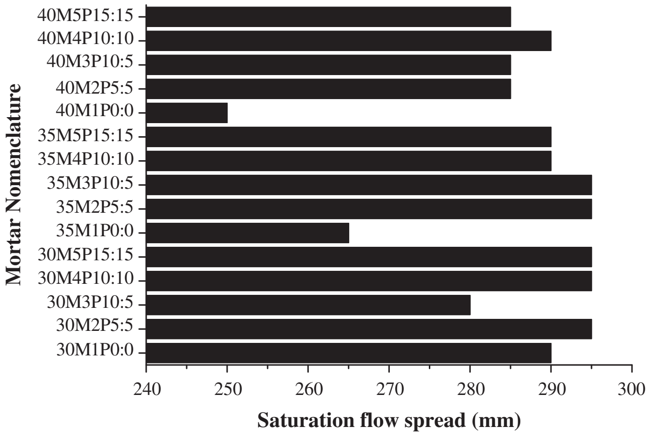

Fig. 6. Saturation flow spread of various mortars in groups 1, 2 and 3.

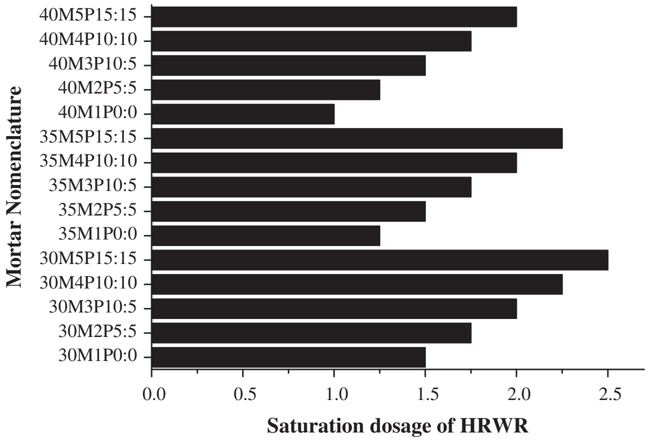

Fig. 7. Saturation dosages of HRWR of various mortars in groups 1, 2 and 3.

higher mortar resistance to flow. It is important to note that, at higher dosages of HRWR (above saturation dosage), 35M2P5:5 and 40M2P5:5 exhibited higher flows spreads, up to 310 mm and 305 mm respectively. Notwithstanding, at higher dosages of HRWR, groups 2 and 3 mortars are prone to bleeding and segregation. The mortars are formulated from a powder based SCC. Therefore, the W/B and the paste volume play a very important role in the flow characteristics of both the mortar and concrete. This, therefore, suggests that for given water content and a fixed W/B, there is an optimum value of powder content that will provide adequate flow characteristics. The same opinion was given by Yahia et al. [35].

3.2. Effect of HRWR on flow spread and relative flow area

Figs. 5 and 6 provide the variation of mortar flow spread and relative flow area for the three different groups of mortars at W/C of 0.30, 0.35 and 0.40, respectively. It can be seen that the mortar flow spread increased with an increase in the dosage of HRWR. This increased level of fluidity of the mortars could be due to the combined effects of liquefying and dispersing actions of the HRWR [7,37]. In addition to the flow spread measurements, visual inspection of the mortars was also carried out (Figs. 8 and 9 and Table 5). It was observed that additional dosage of HRWR, beyond the saturation dosage, resulted in significant bleeding which was indicated by water on the periphery of the spread mortar. The same behaviour has been reported by Safiuddin et al. [7]. Furthermore, no significant increase in flow spread was observed after the saturation dosage, except for 35M1P0:0 and 35M2P5:5 which showed increase of up to 7.5% and 5.1%, respectively. This increase is insignificant because it is associated with bleeding and segregation. No viscosity enhancing admixture was used since PBC was

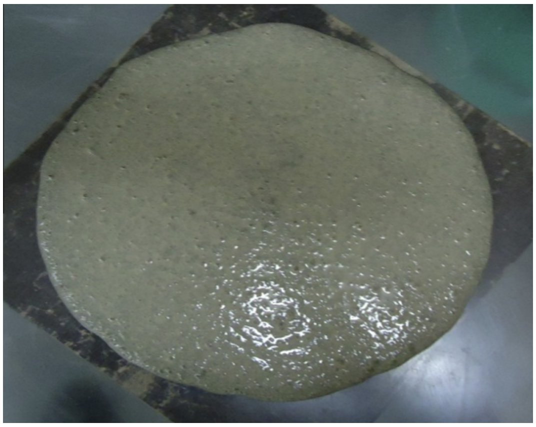

Fig. 8. Flow spread of mortar without bleeding (30M1, 1.50% HRWR).

Table 4
Design mix parameters for the various mortar groups.

Group	Mortar nomenclature	V^{a} ($\times 10^{-3}$ m^3/m^3)	V_b^{b} ($\times 10^{-3}$ m^3/m^3)	A_{sb}^{c} ($\times 10^3$ m^2/m^3)	Sand to binder ratio (S/B)[d]
1	30M1P0:0	343.9	169.7	2701	1.52
	30M2P5:5	343.8	171.6	3105	1.54
	30M3P10:5	343.9	172.8	3570	1.55
	30M4P10:10	343.9	173.5	3500	1.55
	30M5P15:15	343.9	175.4	3886	1.58
2	35M1P0:0	343.8	156.9	2498	1.64
	35M2P5:5	343.9	158.9	2875	1.67
	35M3P10:5	343.8	160.1	3307	1.68
	35M4P10:10	343.9	160.8	3243	1.69
	35M5P15:15	343.8	162.6	3604	1.70
3	40M1P0:0	343.8	146.0	2324	1.77
	40M2P5:5	344.0	148.0	2677	179
	40M3P10:5	343.8	149.1	3081	1.80
	40M4P10:10	343.7	149.7	3022	1.81
	40M5P15:15	343.4	151.4	3356	1.83

[a] Volume fraction of paste.
[b] Volume fraction of binder.
[c] Surface area of binder.
[d] Sand to binder ratio.

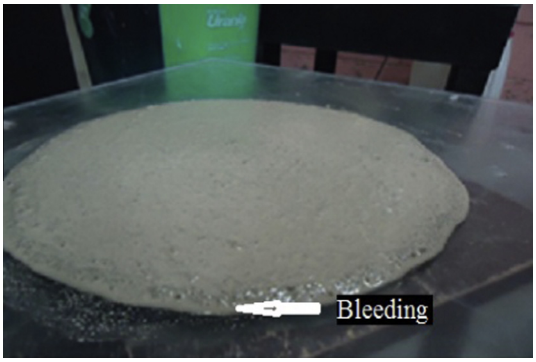

Fig. 9. Flow spread of mortar with bleeding (30M1, 2.0% HRWR).

used as viscosity modifier. This is because all the mortar mixtures were powder based. Consequently, the saturation dosages of the respective mixtures were found adequate. Notwithstanding, some group 3 mortars mixture exhibited evidence of onset of bleeding at the saturation dosages of HRWR, as seen in specimens 40M1P0:0 and 40M2P5:5 (Table 5). This could be attributed to the fact that at higher W/B, the dispersing action of the HRWR is more pronounced due to lower volume fraction of binder and the presence of excess free water.

3.3. Effect of W/B

The W/B plays an important role in the fluidity of mortar mixtures, particularly powder based mixtures. In this study, W/B of 0.3, 0.35 and 0.40 were used for investigation. The flow spreads of mortars were examined for each W/B group at varying percentages of blended POFA and PBC corresponding to the saturation dosages of HRWR (Fig. 6). It can be seen that group 1 mortars with W/B of 0.30 exhibited higher flow spread in comparison to groups 2 and 3. This higher flow spread exhibited by group 1 mortars is due to its improved plasticity and cohesiveness. On the other hand, group 3 mortars exhibited lower plasticity and cohesiveness due to reduced volume fraction of binder and higher S/B. This reduced volume of binder reduces the viscosity of the paste and increases inter-particle friction and induces bleeding. Similar results were also reported by certain authors [3,7,35,36]. As can be seen in visual inspection (Figs. 10 and 11), most of the group 3 mortars showed evidence of the onset of bleeding at saturation dosages of HRWR.

Fig. 10. Flow spread of mortar with onset of bleeding (40M1, 1.0% HRWR).

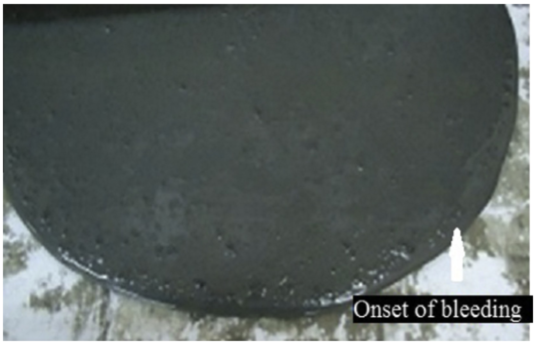

Fig. 11. Flow spread of mortar with onset of bleeding (40M5, 2.25% HRWR).

3.4. Effect of blend of POFA and PBC

Investigations on the microstructure of POFA and PBC carried out by Hassan et al. [38] showed that POFA has a high BET surface area (23.75 m^2/g) while PBC has a very low surface area (2.98 m^2/g) compared to OPC with BET surface area (5.07 m^2/g). The addition of POFA at varying percentages increased the viscosity of the mixes. This is particularly due to dispersed arrangement of particles as well as porous and irregularly shaped particles (Fig. 12). Although POFA and PBC carry relatively similar particle size distribution (Table 2), the addition of PBC into the mixtures tends to

Table 5
Visual inspection results for the various mortar groups.

Mortar nomenclature	HRWR dosage (%B)		Physical observation on the flow spread of mortar
	Sd[a]	Ud[b]	
30M1P0:0	1.50	1.00–2.50	Bleeding at and after 2.0% HRWR
30M2P5:5	1.75	1.00–2.50	No bleeding
30M3P10:5	2.00	1.50–3.00	No bleeding
30M4P10:10	2.25	1.50–3.00	No bleeding
30M5P15:15	2.50	1.75–3.00	No bleeding
35M1P0:0	1.25	1.00–2.50	Bleeding at and after 1.5% HRWR
35M2P5:5	1.50	1.00–2.50	Bleeding at and after 1.75% HRWR
35M3P10:5	1.75	1.25–2.50	Bleeding at and after 2.0% HRWR
35M4P10:10	2.00	1.50–3.00	Bleeding at and after 2.25% HRWR
35M5P15:15	2.25	1.50–3.00	Bleeding at and after 2.75% HRWR
40M1P0:0	1.00	1.00–2.50	Onset of bleeding at 1.0% HRWR
40M2P5:5	1.25	1.00–2.50	Onset of bleeding at 1.25% HRWR
40M3P10:5	1.50	1.00–2.50	Bleeding at and after 1.75% HRWR
40M4P10:10	1.75	1.00–2.50	Bleeding at and after 2.0% HRWR
40M5P15:15	2.00	1.00–2.50	Bleeding at and after 2.25% HRWR

[a] Saturation dosage of HRWR.
[b] Used dosage of HRWR.

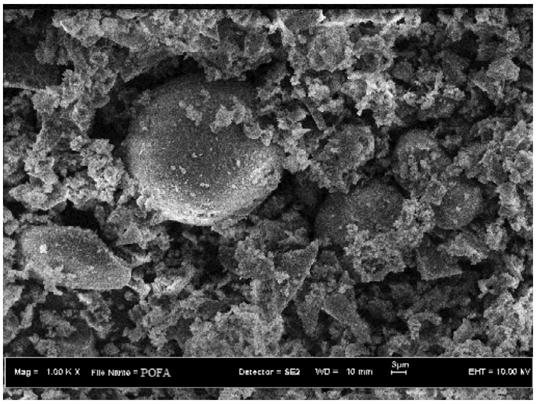

Fig. 12. SEM image showing dispersed and porous particles of POFA.

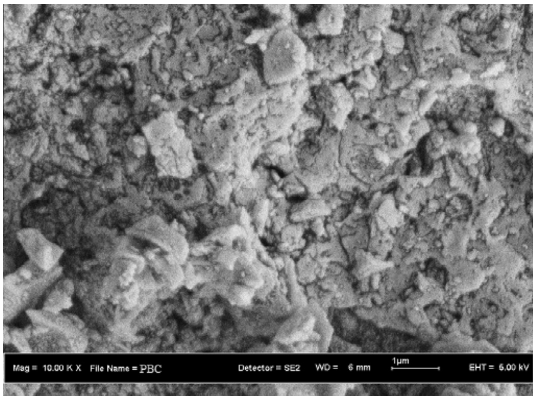

Fig. 13. SEM image showing agglomerated particles arrangement of PBC.

improve the rheology of the mixtures. This is particularly due to agglomerated particles arrangement and high content of non-porous glassy surfaced particles characterised by high calcination temperature (Fig. 13). Thus, it reduces the demand for higher percentages of HRWR while increasing the flow spread. Furthermore, Table 5 shows that the addition of a blend of POFA and PBC prevented the bleeding of the mortars at higher dosages of HRWR. It was also observed that there is no significant difference in the flow spread because the blend was based predominantly on equal proportion of SCM, except for the M3 series which were based on 10% POFA and 5% PBC.

The increased volume fraction and surface area of binder requires higher dosages of HRWR at higher percentage of POFA to obtain the saturation flow spread. The dosage of HRWR is reduced by the inclusion of PBC. The extent of flow spread also depends on the physical and micro-structural characteristics of the binder. A comparative assessment carried out by Safiuddin et al. [7] showed that fly ash (FA) and silica fume (SF) have spherical and non-porous particles while rice husk ash (RHA) has angular and porous particles. The physical characteristics of FA and SF are responsible for greater flow spread in comparison with RHA. A blend of POFA and PBC has demonstrated similar flow spread characteristics as FA and SF. These results are also in agreement with the findings of previous research carried out on ternary mixtures where by, one mineral additive is used to hinder the negative effects of the other one, thus yielding a SFCM with the required flow characteristics [39].

The HRWR requirement of the binder was higher for lower W/B for the same percentage replacement. At 20% and 30% replacements, the saturation dosages of HRWR were 2.25/2.5, 2.00/2.25 and 1.75/2.00 for W/B of 0.3, 0.35 and 0.40, respectively. On the other hand, the saturation flow spreads were 295 mm/295 mm, 290 mm/290 mm and 290 mm/285 mm, respectively.

3.5. Significance of the flow spread results of mortars

As has been advocated, the flow characteristic of mortar is greatly influenced by 3 key factors which include; HRWR dosage, powder content and W/B. The results of this investigation are very useful for adequate proportioning of HRWR dosage, appropriate content of the blend of POFA and PBC and W/B for various SCC mixtures.

4. Conclusions

Based on the results of the study on the flow characteristics of various mortars containing a blend of OPC, POFA and PBC and formulation of various SCC mixtures, the following conclusions can be drawn:

a. The flow spread of mortar increases with the increase dosage of HRWR due to deflocculating and dispersing behaviour of the powders particles.
b. The flow spread of various mortars did not increase significantly at higher dosages of HRWR beyond the saturation dosage. Instead, visual inspection identified the manifestation of bleeding at such higher dosages.
c. The mix compositions and parameters, such as, variation in the volume fractions of binder, its surface area, volume fraction of paste and S/B greatly influenced the flow spread of the various mortars studied.
d. Group 1 mortars with W/B of 0.30 exhibited higher flow spread than groups 2 and 3 with W/B of 0.35 and 0.4, respectively. Group 1 mortars exhibited higher viscosity than group 2 due to higher volume fraction of binder and its surface area. On the other hand, group 3 mortars exhibited lower viscosity due to lower volume fraction of binder and lower surface area.
e. The physical and micro-structural characteristics of the SCMs played a very important role in the demand of HRWR in the investigation of various mortars.
f. The addition of a blended POFA and PBC prevented the bleeding of the mortars at higher dosages of HRWR. The flow spread of the mortars increased with the increase percentage of blended POFA and PBC. However, no significant difference was observed in the flow spread because the blend was based on equal proportions of POFA and PBC.
g. A blend of up to 30% (15% POFA and 15% PBC) was found appropriate for all groups of mortars since there is no significant difference in the flow spread at such higher replacement levels. A slight delay in setting time was observed in group 1 mortars incorporating 2.5% HRWR. In general, all mortar mixes showed good level of workability in terms of mixing and handling.
h. The results of flow spread were useful to select appropriate dosages of HRWR for the respective mortars and consequently the parent SCCs.

Acknowledgements

The authors wish to express their profound gratitude for the financial contribution from MOSTI research Grant No. 03-01-06-SF1217, the research management centre of Universiti Teknologi

Malaysia (RMC, UTM) and the technical support provided by the laboratory technician of the Faculty of Civil Engineering.

References

[1] Vachon M, Daczko J, U.S regulatory work on SCC in proceedings of the first North American conference on the design and use of self-consolidating concrete. Evanston, USA; 2002.
[2] ACI-113R. Cement and concrete terminology, ACI: Detroit, USA; 1990.
[3] Okamura H, Ozawa K. Mix design for self-compacting concrete. Conc Library JSCE 1995;25:107–20.
[4] Okamura H, Ouchi M. Self-compacting concrete. J Adv Concr Technol 2003;1(1):5–15.
[5] Lachemi M, Hossain KMA, Patel R, Shehata M, Bouzoubaa N. Influence of paste/mortar rheology on the flow characteristics of high-volume fly ash selfconsolidating concrete. Mag Concr Res 2007;59(7):517–28.
[6] EFNARC. Specifications and guidelines for self-compacting concrete. Surrey, UK; 2002.
[7] Safiuddin M, West JS, Soudki KA. Flowing ability of the mortars formulated from self-compacting concretes incorporating rice husk ash. Constr Build Mater 2011;25(2):973–8.
[8] Barbhuiya S. Effects of fly ash and dolomite powder on the properties of self-compacting concrete. Constr Build Mater 2011;25(8):3301–5.
[9] Turk K. Viscosity and hardened properties of self-compacting mortars with binary and ternary cementitious blends of fly ash and silica fume. Constr Build Mater 2012;37:326–34.
[10] Safiuddin M, West JS, Soudki KA. Properties of freshly mixed self-consolidating concretes incorporating rice husk ash as a supplementary cementing material. Constr Build Mater 2012;30:833–42.
[11] Barluenga G, Hernández-Olivares F. Self-levelling cement mortar containing grounded slate from quarrying waste. Constr Build Mater 2010;24(9):1601–7.
[12] Tangchirapat W, Jaturapitakkul C, Chindaprasirt P. Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete. Constr Build Mater 2009;23(7):2641–6.
[13] Sumadi SR, Hussin MW. Palm oil fuel ash (POFA) as a future partial cement replacement material in housing construction. J Ferrocement 1995;25(1):25–34.
[14] Ismail ME, Hussin MW, Ismail M. Palm oil fuel ash as the future supplementary cementitious material in concrete. Concr Plant Int 2010;3:38–45.
[15] Jordán MM, Boix A, Sanfeliu T, de la Fuente C. Firing transformations of cretaceous clays used in the manufacturing of ceramic tiles. Appl Clay Sci 1999;14(4):225–34.
[16] Pardo F, Meseguer S, Jordán MM, Sanfeliu T, González I. Firing transformations of Chilean clays for the manufacture of ceramic tile bodies. Appl Clay Sci 2011;51(1–2):147–50.
[17] Wild S, Khatib JM, O'Farrell M. Sulphate resistance of mortar, containing ground brick clay calcined at different temperatures. Cem Concr Res 1997;27(5):697–709.
[18] Sabir BB, Wild S, Bai J. Metakaolin and calcined clays as pozzolans for concrete: a review. Cem Concr Compos 2001;23(6):441–54.
[19] O'Farrell M, Wild S, Sabir BB. Resistance to chemical attack of ground brick–PC mortar: Part II. Synthetic seawater. Cem Concr Res 2000;30(5):757–65.
[20] O'Farrell M, Sabir BB, Wild S. Strength and chemical resistance of mortars containing brick manufacturing clays subjected to different treatments. Cem Concr Compos 2006;28(9):790–9.
[21] Page I. The rise and fall of claddings, in build, June/July 2007. p. 68–9.
[22] RMIT. Scoping study to investigate measures for improving the environmental sustainability of building materials, 2006, Australian Greenhouse Office, Commonwealth of Australia, Melbourne, Australia; 2006.
[23] P Crowther 23. Building deconstruction in Australia. In: Chini CJKaAR, editor. Overview of deconstruction in selected countries. Florida: University of Florida; 2000. p. 1–28.
[24] Formoso C, Soibelman MASCE Lucio, De Cesare Claudia, Isatto Eduardo L. Material waste in building industry: main causes and prevention. J Constr Eng Manage 2002;128(4):316–25.
[25] Demir I, Orhan M. Reuse of waste bricks in the production line. Build Environ 2003;38(12):1451–5.
[26] Kharrufa S. Reduction of building waste in Baghdad Iraq. Build Environ 2007;42(5):2053–61.
[27] Safiuddin 27M, Abdus-Salam M, Jumaat M. Key fresh properties of self-consolidating high-strength POFA concrete. J Mater Civil Eng 2013;0(ja).
[28] Heikal M, Zohdy KM, Abdelkreem M. Mechanical, microstructure and rheological characteristics of high performance self-compacting cement pastes and concrete containing ground clay bricks. Constr Build Mater 2013;38:101–9.
[29] ASTM C150/C150M. Standard specification for Portland cement, in Annual Book of ASTM Standards, vol. 04.02 2012, American Society for Testing and Materials: Philadelphia, USA. p. 9.
[30] ASTM C494/C494M. Standard specification for chemical admixtures for concrete, in Annual Book of ASTM Standards, vol. 04.02 2013, American Society for Testing and Materials: Philadelphia, USA. p. 10.
[31] ASTM C305. Standard practice for mechanical mixing of hydraulic cement pastes and mortars of plastic consistency, in Annual Book of ASTM Standards, vol. 04.02 2012, American Society for Testing and Materials: Philadelphia, USA. p. 3.
[32] Safiuddin M, West JS, Soudki KA. Flowing ability of self-consolidating concrete and its binder paste and mortar components incorporating rice husk ash. Can J Civ Eng 2010;37(3):401–12.
[33] Domone P. Mortar tests for self-consolidating concrete. Concr Int 2006;28(4):39–45.
[34] ASTM C230/C230M. Standard specification for flow table for use in tests of hydraulic cement, in Annual Book of ASTM Standards, vol. 04.02 2008, American Society for Testing and Materials: Philadelphia, USA. p. 6.
[35] Yahia A, Tanimura M, Shimoyama Y. Rheological properties of highly flowable mortar containing limestone filler-effect of powder content and W/C ratio. Cem Concr Res 2005;35(3):532–9.
[36] Lane RO, Best JF. Properties and use of fly ash in Portland cement concrete. Concr Int 1982;4(7):81–92.
[37] De Schutter G, Bartos PJM, Domone P, Gibbs J. Self-compacting concrete. Scotland, UK: Whittles Publishing; 2008. 296.
[38] Hassan IO, Ismail M, Noruzman AH, Yusuf TO, Mehmannavaz T, Usman J. Characterization of some key industrial waste products for sustainable concrete production. Adv Mater Res 2013;690–693:1091–4.
[39] Şahmaran M, Christianto HA, Yaman İÖ. The effect of chemical admixtures and mineral additives on the properties of self-compacting mortars. Cem Concr Compos 2006;28(5):432–40.