Effect of Blended Palm Oil Fuel Ash and Pulverised Burnt Clay Bricks on the Flowing Ability of Self-Consolidating Binder Paste

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Abstract

This paper presents the flowing ability of binder pastes formulated from series of binary and ternary blended self-consolidating concrete incorporating blended palm oil fuel ash (POFA) and pulverised burnt clay bricks (PBC). Three series of binder paste were produced using various percentages of blended POFA and PBC at different water to binder ratios (W/B). The first series was produced with different dosages of class F polycarboxylic based high range water reducer (HRWR), the second series was produced without HRWR but at varying water content. The water content of the third series was based on standard consistency. The effect of HRWR, binary and ternary blend of Ordinary Portland cement (OPC), POFA and PBC and W/B ratio on the flowing ability of the binder paste were observed. The result shows that the flowing ability of both series increases with an increase in the HRWR dosage, water content and up to 20% PBC content; the flowing ability decreases at lower W/B ratio, higher POFA content and higher blended POFA and PBC content. A blend of POFA and PBC of up 30% with a HRWR saturation dosage of ≤ 2.5% is considered suitable for the production of self-consolidating paste and concrete with W/B ≤ 3.0 and up to 0.40.

Keywords: Binder paste; Flowing ability; Palm oil fuel ash; Pulverised burnt clay; Self-consolidating.

1.0 Introduction

The characteristics of self-consolidating concrete (SCC) are influenced primarily by the characteristics of its paste components. This is basically due to the fact that the concrete consist of two main parts, namely, the aggregate skeleton and the paste matrix. Adequately proportioning these two parts is the key to successful design of SCC. Consequently, many researches have been carried out to study the behaviour of the binder paste. This is to facilitate the mix design process and to achieve the desirable characteristics in the parent SCC (EFNARC, 2002; Lachemi, *et al*, 2007; Nunes, *et al*. 2011; Safiuddin, West, & Soudki, 2010; Safiuddin, West, & Soudki, 2011b).

Generally, the flow characteristics of SCC are determined by the rheological properties of paste, volumetric fraction of aggregate and particle size distribution (Saak, Jennings, & Shah, 2001; Tang, *et al*. 2001). To achieve the desired flow ability, high range water reducer (HRWR) and appropriate quantity of supplementary cementing materials (SCM) are used. This ensures the achievement of excellent flowing ability in the binder paste (Safiuddin, *et al*., 2011b). HRWR enhances the flowing ability of the binder paste and the SCC by reducing the yield stress and plastic viscosity (Cyr & Mouret, 2003). This reduced level of resistance to flow is as a result of the combined effects of liquefying and dispersing action of the HRWR (De Schutter, *et al*. 2008; Safiuddin, West, & Soudki, 2011c). Notwithstanding, the use of excessive dosage of HRWR, may induce bleeding and segregation. Previous researches have shown that SCM such as fly ash, ground granulated blast furnace slag, silica fume and rice husk ash have been used in binder paste (Domone, 2006; Safiuddin, *et al*., 2011b; Toutanji & El-Korchi, 1996). In comparison, the use of POFA and PBC is very limited.

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 to generate electricity (Tangchirapat, Jaturapitakkul, & Chindaprasirt, 2009). In Malaysia alone, about 3 million tons of ash are generated annually. This quantity of ash is usually dumped on open fields, constituting environmental pollution and health hazard problems (Ismail, Hussin, & Ismail, 2010; Sumadi & Hussin, 1995). On the other hand, 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 (Page, 2007; RMIT, 2006). 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 in open landfills. Hence, they contribute significantly to the environmental health hazard (Crowther, 2000; Demir & Orhan, 2003; Formoso, *et al*. 2002; Kharrufa, 2007).

The use of POFA and PBC as a binder paste in the production of SCC will go a long way in solving waste disposal problems. It also has the potential of reducing the overall cost of concrete production. Although limited research have been carried out on the use of POFA and PBC in the production of SCC (Heikal, Zohdy, & Abdelkreem, 2013; Safiuddin, Abdus-Salam, & Jumaat, 2011a; Safiuddin, Abdus-Salam, & Jumaat, 2013), there is no any published literature on the use of blended POFA and PBC as a binder paste in the production of SCC. In fact, no study has been conducted to investigate the effects of blended POFA and PBC on the flowing ability and other key fresh properties of binder paste and SCC. The present study investigated the effects of blended POFA and PBC, HRWR content and W/B on the flowing ability of the formulated binder paste. The study also determined the water demand of the blended binders, the water reduction capacity and the saturation dosages of the HRWR at different percentages of blending. This study also presented the suitability of the use of blended POFA and PBC and the significance of the results of flowing ability of the binder paste in the design and production of SCC. The significance of this research is the evaluation of the meaningful contribution of HRWR in reducing the W/B ratio in SCHPC containing SCM with very high surface area. Above all, enhances achieving required hardened properties while maintaining the desired fresh characteristics.

2 Experimental

Ordinary Portland cement (OPC), conforming to ASTM C150/C150M (2012) specification, a blend of POFA and PBC conforming to ASTM C618 (2012) specification and normal tap water (W) were used to produce various groups of binder pastes. The superplasticizer used was a polycarboxylic based HRWR conforming to ASTM C494/C494M (2013) specification. Both the POFA and PBC were obtained from the southern part of Malaysia. The physical and the chemical properties of the respective binders are as presented in Tables 1 and 2.

Table 1 Physical properties of the constituent materials

Material	Properties
Fine aggregate	specific gravity on saturated surface dry bases : 2.55 absorption : 1.8% total evaporable moisture content: 1.0% finess 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): 5.067m²/g
Palm oil fuel ash (POFA)	Specific gravity: 2.42 percentage passing 45-µm wet sieve: 98.4% specific surface area (BET): 23.7514m²/g
Pulverised burnt clay brick (PBC)	Specific gravity: 2.69 percentage passing 45-µm wet sieve: 96.4% specific surface area (BET): 2.9791m²/g
high range water reducer (HRWR)	Specific gravity: 1.10 pH value: 8 Solid content: 42%

Table 2 Chemical properties of the respective binders

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

2.1 Preparation of binder pastes

In this study, three series of binder pastes were prepared. The first two series were based on the mix design of the parent SCC. On the other hand, the third series was based on the standard consistency as specified by ASTM C187-11e1 (2011). The first series consists of 27 different mixtures of binder pastes that were formulated based on W/B of 0.3, 0.35 and 0.40, with a blended POFA and PBC as SCM at a replacement level ranging between 0 and 30% (tables 3-6). HRWR was used in the preparation of series 1 paste at an incremental quantity until saturation. On the other hand, series 2 pastes were prepared based on the same W/B and percentage replacement levels as in series 1 paste. In the case of series 2 paste, no HRWR was used. Instead, a certain percentage of mixing water was added incrementally, to achieve similar flow as in series 1. Series 1 binder paste as shown in Table 3 were prepared in order to investigate the flowing ability at various dosages of HRWR and to determine the saturation dosages. The dosages below the saturation point were employed to ensure continuous flow. On the other hand, dosages above the saturation point were employed to produce flow beyond the saturation flow of the binder paste. Series 2 binder pastes as shown in Table 4 were prepared in order to test the flowing ability at various water contents and consequently, determine the water reduction capacity of HRWR and the water demand of the blended POFA and PBC. In both series, the water content (W) and the binder content (B) were varied based on the selected W/B.

Table 3 Mixture composition of series 1 paste

Paste Nomenclature	POFA (% of B[a])	PBC (% of B[a])	W/B Ratio	Cement (kg)	POFA (kg)	PBC (kg)	Water (kg)	HRWR (% of B[a])
30P1SE1	0	0	0.3	4.57	0.00	0.00	1.37	0.25-2.00
30P2SE1	5	5	0.3	4.06	0.23	0.23	1.35	0.50-3.00
30P3SE1	5	5	0.3	3.81	0.45	0.22	1.34	0.75-3.00
30P4SE1	10	10	0.3	3.57	0.45	0.45	1.34	0.75-4.00
30P5SE1	15	15	0.3	3.09	0.66	0.66	1.32	0.75-4.00
30P6SE1	0	10	0.3	4.08	0.00	0.45	1.36	0.25-2.00
30P7SE1	0	20	0.3	3.59	0.00	0.90	1.35	0.25-2.00
30P8SE1	10	0	0.3	4.05	0.45	0.00	1.35	0.25-3.00
30P9SE1	20	0	0.3	3.55	0.89	0.00	1.33	0.75-4.00
35P1SE1	0	0	0.3	4.23	0.00	0.00	1.48	0.25-2.00
35P2SE1	5	5	0.3	3.76	0.21	0.21	1.46	0.50-3.00
35P3SE1	10	5	0.3	3.53	0.42	0.21	1.45	0.75-3.00
35P4SE1	10	10	0.3	3.31	0.41	0.41	1.45	0.75-3.00
35P5SE1	15	15	0.3	2.86	0.61	0.61	1.43	0.75-3.50
35P6SE1	0	10	0.3	3.77	0.00	0.42	1.47	0.25-2.00
35P7SE1	0	20	0.3	3.33	0.00	0.83	1.46	0.25-2.00
35P8SE1	10	0	0.3	3.75	0.42	0.00	1.46	0.25-2.50
35P9SE1	20	0	0.3	3.29	0.82	0.00	1.44	0.75-3.50
40P1SE1	0	0	0.3	3.93	0.00	0.00	1.57	0.25-2.00
40P2SE1	5	5	0.3	3.5	0.19	0.19	1.56	0.50-2.50
40P3SE1	10	5	0.3	3.29	0.39	0.19	1.55	0.75-3.00
40P4SE1	10	10	0.3	3.08	0.39	0.39	1.54	0.75-3.00
40P5SE1	15	15	0.3	2.66	0.57	0.57	1.52	0.75-3.50
40P6SE1	0	10	0.3	3.51	0.00	0.39	1.56	0.25-2.00
40P7SE1	0	20	0.3	3.1	0.00	0.77	1.55	0.25-2.00
40P8SE1	10	0	0.3	3.49	0.39	0.00	1.55	0.25-2.50
40P9SE1	20	0	0.3	3.06	0.77	0.00	1.53	0.50-3.50

[a] Binder

Table 4 Mixture composition of series 2 paste

Paste Nomenclature	POFA (% of B[a])	PBC (% of B[a])	W/B Ratio	Cement (kg)	POFA (kg)	PBC (kg)	Water (kg)	Additional water (% of W[b])
30P1SE2	0	0	0.3	4.57	0.00	0.00	1.37	30-80
30P2SE2	5	5	0.3	4.06	0.23	0.23	1.35	40-90
30P3SE2	10	5	0.3	3.81	0.45	0.22	1.34	50-100
30P4SE2	10	10	0.3	3.57	0.45	0.45	1.34	50-100
30P5SE2	15	15	0.3	3.09	0.66	0.66	1.32	50-100
30P6SE2	0	10	0.3	4.08	0.00	0.45	1.36	30-80
30P7SE2	0	20	0.3	3.59	0.00	0.90	1.35	30-80
30P8SE2	10	0	0.3	4.05	0.45	0.00	1.35	50-100
30P9SE2	20	0	0.3	3.55	0.89	0.00	1.33	60-120
35P1SE2	0	0	0.35	4.23	0.00	0.00	1.48	25-75
35P2SE2	5	5	0.35	3.76	0.21	0.21	1.46	35-85
35P3SE2	10	5	0.35	3.53	0.42	0.21	1.45	45-95
35P4SE2	10	10	0.35	3.31	0.41	0.41	1.45	45-95
35P5SE2	15	15	0.35	2.86	0.61	0.61	1.43	45-95
35P6SE2	0	10	0.35	3.77	0.00	0.42	1.47	25-75
35P7SE2	0	20	0.35	3.33	0.00	0.83	1.46	25-75
35P8SE2	10	0	0.35	3.75	0.42	0.00	1.46	45--95
35P9SE2	20	0	0.35	3.29	0.82	0.00	1.44	55-115
40P1SE2	0	0	0.40	3.93	0.00	0.00	1.57	20-70
40P2SE2	5	5	0.40	3.5	0.19	0.19	1.56	30-80
40P3SE2	10	5	0.40	3.29	0.39	0.19	1.55	40-90
40P4SE2	10	10	0.40	3.08	0.39	0.39	1.54	40-90
40P5SE2	15	15	0.40	2.66	0.57	0.57	1.52	40-90
40P6SE2	0	10	0.40	3.51	0.00	0.39	1.56	20-70
40P7SE2	0	20	0.40	3.1	0.00	0.77	1.55	20-70
40P8SE2	10	0	0.40	3.49	0.39	0.00	1.55	40-90
40P9SE2	20	0	0.40	3.06	0.77	0.00	1.53	50-100

The third series of paste were prepared by initially mixing 650g of cement with an incremental quantity of water ranging from 26% to 33%, which corresponded to W/B of 0.26 to 0.33. Subsequently,the cement was replaced with 10, 15, 20 and 30% blends of POFA and PBC, while maintaining the same W/B to produce the ternary blended pastes. In addition, the cement was replaced with 10 and 20% each of POFA and PBC at the same W/B to produce the binary blended pastes (Table 6). Furthermore, the third series of paste were prepared in order to test the water demand of the respective powders in binary and ternary blends and to determine the effect of the blend on the setting time of the pastes.

For each of the series, 3L of pastes was prepared using the medium sized epicyclic revolving type mixer, conforming to ASTM C305 (2012) specification.

Table 5 Saturation flow time, saturation dosage and water reduction capacity of HRWR, and water demand of binary and ternary blend of OPC, POFA and PBC

Paste Nomenclature	POFA (% of B[a])	PBC (% of B[a])	W/B Ratio	Saturation dosage of HRWR (%B[a])	Saturation flow time (s)	Water reduction capacity of HRWR	Water demand of B[a](%)
30P1P0:0	0	0	0.3	1.50	15.03	32.58	0.00
30P2P5:5	5	5	0.3	1.75	15.32	35.93	7.80
30P3P10:5	10	5	0.3	2.00	16.54	39.15	16.00
30P410:10	10	10	0.3	2.25	16.20	38.15	14.10
30P5P15:15	15	15	0.3	2.50	17.80	41.15	21.06
30P6P0:10	0	10	0.3	1.00	14.29	31.59	-2.10
30P7P0:20	0	20	0.3	1.00	14.62	29.06	-6.30
30P8P10:0	10	0	0.3	1.75	16.27	39.40	17.22
30P9P20:0	20	0	0.3	2.50	18.66	45.09	33.81
35P1P0:0	0	0	0.35	1.25	13.04	30.15	0.00
35P2P5:5	5	5	0.35	1.50	13.30	33.70	7.60
35P3P10:5	10	5	0.35	1.75	14.50	37.12	15.80
35P4P10:10	10	10	0.35	2.00	14.25	36.32	13.80
35P5P15:15	15	15	0.35	2.25	16.20	39.17	21.20
35P6P0:10	0	10	0.35	0.75	12.48	28.81	-2.70
35P7P0:20	0	20	0.35	0.75	12.90	26.85	-6.50
35P8P10:0	10	0	0.35	1.50	14.29	37.98	18.00
35P9P20:0	20	0	0.35	2.25	16.72	43.35	33.30
40P1P0:0	0	0	0.40	1.00	11.40	27.55	0.00
40P2P5:5	5	5	0.40	1.25	11.32	31.28	7.50
40P3P10:5	10	5	0.40	1.50	12.60	34.85	15.50
40P4P10:10	10	10	0.40	1.75	12.30	34.13	13.80
40P5P15:15	15	15	0.40	2.00	14.20	37.11	21.00
40P6P0:10	0	10	0.40	0.50	10.80	26.10	-2.70
40P7P0:20	0	20	0.40	0.50	10.95	23.83	-6.70
40P8P10:0	10	0	0.40	1.25	12.65	35.90	18.00
40P9P20:0	20	0	0.40	2.00	15.11	40.99	31.50

[a] Binder

Table 6 Mixture composition of series 3 paste, consistency and water demand of binary and ternary blend of OPC, POFA and PBC

Paste Nomenclature	POFA (% of B[a])	PBC (% of B[a])	Cement (g)	POFA (g)	PBC (g)	Consistency (% 0f B[a])	Weight of water (g)	Water demand of B[a] (%)
P1SE3	0	0	650.00	0.00	0.00	0.27	175.50	0.00
P2SE3	5	5	585.00	32.50	32.50	0.28	182.00	3.70
P3SE3	10	5	552.50	65.00	32.50	0.30	195.00	11.11
P4SE3	10	10	520.00	65.00	65.00	0.29	188.50	7.41
P5SE3	15	15	455.00	97.50	97.50	0.31	201.50	14.80
P6SE3	0	10	585.00	0.00	65.00	0.27	175.50	0.00
P7SE3	0	20	520.00	0.00	130.00	0.26	169.00	-3.70
P8SE3	10	0	585.00	65.00	0.00	0.30	195.00	11.11
P9SE3	20	0	520.00	130.00	0.00	0.31	201.50	14.80

[a] Binder

2.2 Test on the respective properties of binder pastes

Two different methods were employed to evaluate the flowing ability of the binder pastes. The first method involves determining the time of flow of the respective binder paste at an incremental dosage of HRWR from 0.25 up to 4.0% by weight of binder, while, the second method involves determining the time of flow of the respective binder paste at an incremental quantity of water, from 20 up to 120% by weight of the mixing water. In both methods, a standard flow cone, conforming to ASTM C 939 (2010) was used to determine the flow time of the respective binder pastes (Fig. 1). A third method was employed to determine the water demand of the blended POFA and PBC based on the standard consistency as specified by ASTM C187-11e1 (2011). This method involves the determination of the consistency of the freshly prepared paste by using the Vicat apparatus at an incremental quantity of water from 0.26 up to 0.33% of the binder. The paste is said to have achieved normal consistency when the Vicat rod settles to a point 10± 1 mm below the original surface in 30 s after being released. The paste was also used to determine the setting time of the paste based on ASTM C191 (2013) guideline (which outside the scope of this paper).

Fig. 1 Flow cone test of binder paste

3 Results and discussion

Figs. 2 and 3 shows the results of the flow cone test for various binder pastes under series 1 and 2. Fig. 2 indicates the flowing ability of series 1 binder pastes with respect to the flow time at various dosages of HRWR. Fig. 3 shows the flowing ability of series 2 binder paste with respect to flow time at an incremental quantity of water without any HRWR.Table 6 presented the result of the standard consistency of series 3 binder paste with respect to the penetration of the Vicat rod.

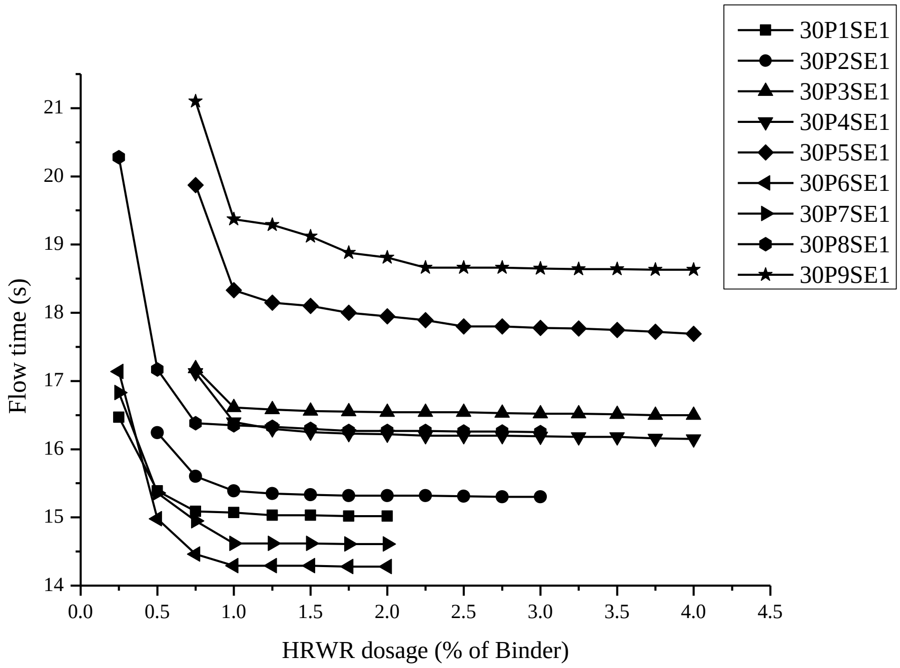

Fig. 2(a): W/B = 0.3

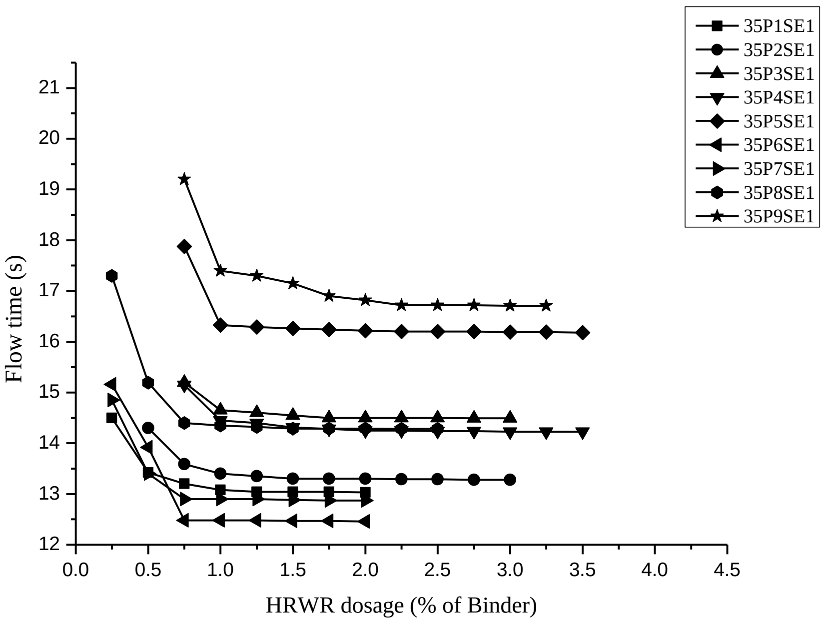

Fig. 2(b): W/B = 0.35

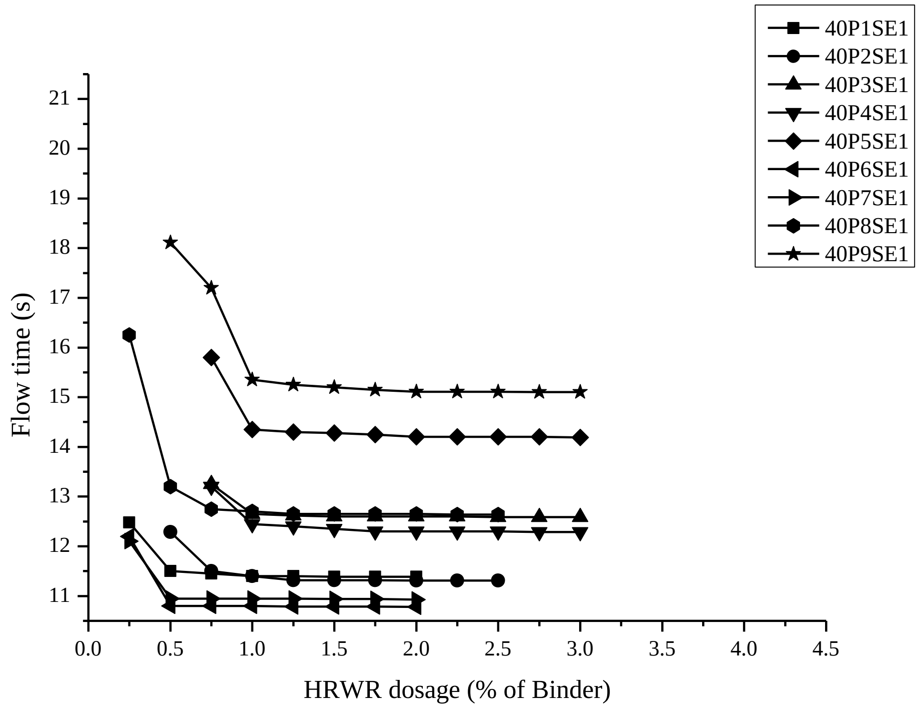

Fig. 2(c): W/B = 0.40

Fig. 2 (a, b, c) Flow time of series 1 binder paste at different dosages of HRWR

3.1 Effect of HRWR

The effect of HRWR on the flowing ability of the binder pastes is as shown in Fig. 2. As can be seen, the flowing ability increases as the flow time of the binder paste decreases. The decrease in the flow time is as a result of increase in the dosage of HRWR. It is particularly due to the reduction in the plastic viscosity of the binder paste. The plastic viscosity of the binder paste decreases due to the liquefying characteristics of the HRWR. On the other hand, its dispersing characteristics, causes the binder particles to be deflocculated and dispersed more evenly, thereby, enhancing the flowing ability. Similar behaviour was also reported by Heikal, Zohdy & Abdelkreem (2013).

3.2. Saturation Dosage of HRWR

The flow time of the binder paste becomes relatively constant (< 3%) after a particular dosage of HRWR. This dosage is referred to as the saturation point. After the saturation dosage, any addition of HRWR does not have any significant effect on the flow time of the respective binder pastes. This characteristic flow is as shown in Fig. 2.

The saturation dosages of the various binder pastes are as provided in Table 5. As can be seen in Fig. 4, the saturation dosages of the HRWR were influenced by the W/B and the content of the blended POFA and PBC. The binary blend of OPC and PBC requires lesser dosage of HRWR to attain saturation flow, as compared with a binary blend of OPC and POFA at the same W/B and percentage replacement. This is due to the flocculation forces and the water reduction tendencies of the PBC. Generally, at lower W/B and higher content of blended POFA and PBC, the demand for HRWR increases. This is because the flocculation forces become greater at lower W/B and higher content of SCM, particularly POFA that has a higher surface area and particles that are porous in nature. Similar characteristics were reported by Safiuddin, *et al*. (2011b) to be exhibited by binder paste containing rice husk ash, which has particles that are also porous.

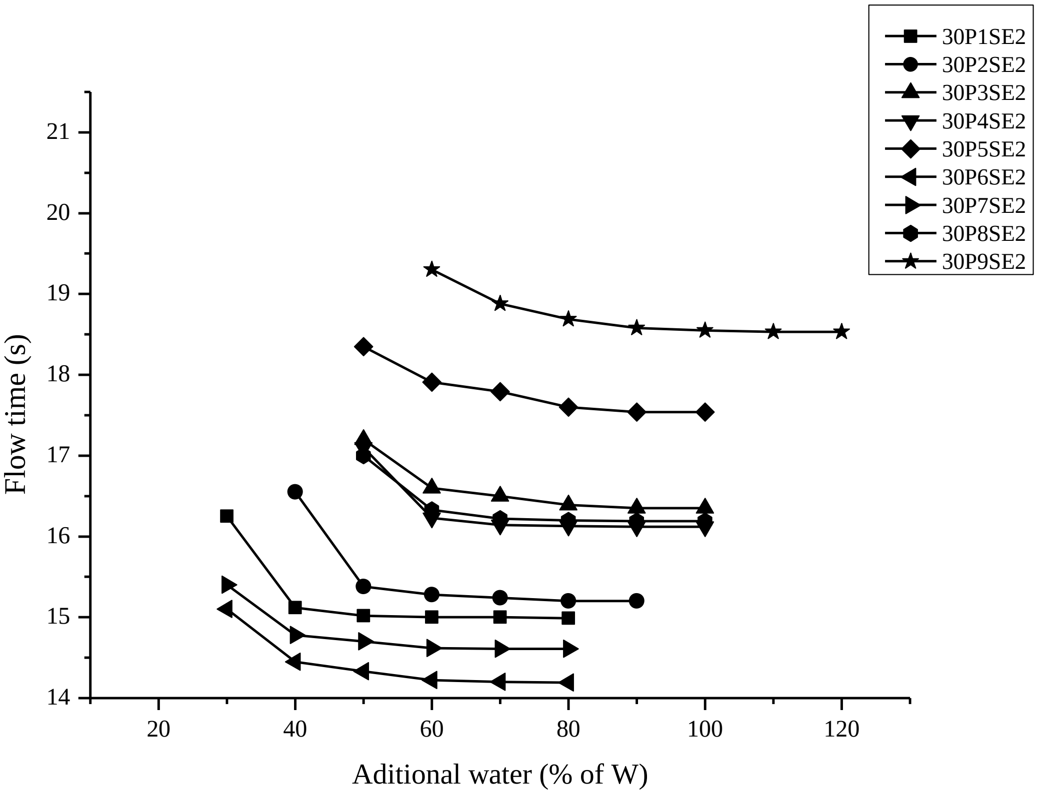

Fig. 3(a): W/B = 0.30

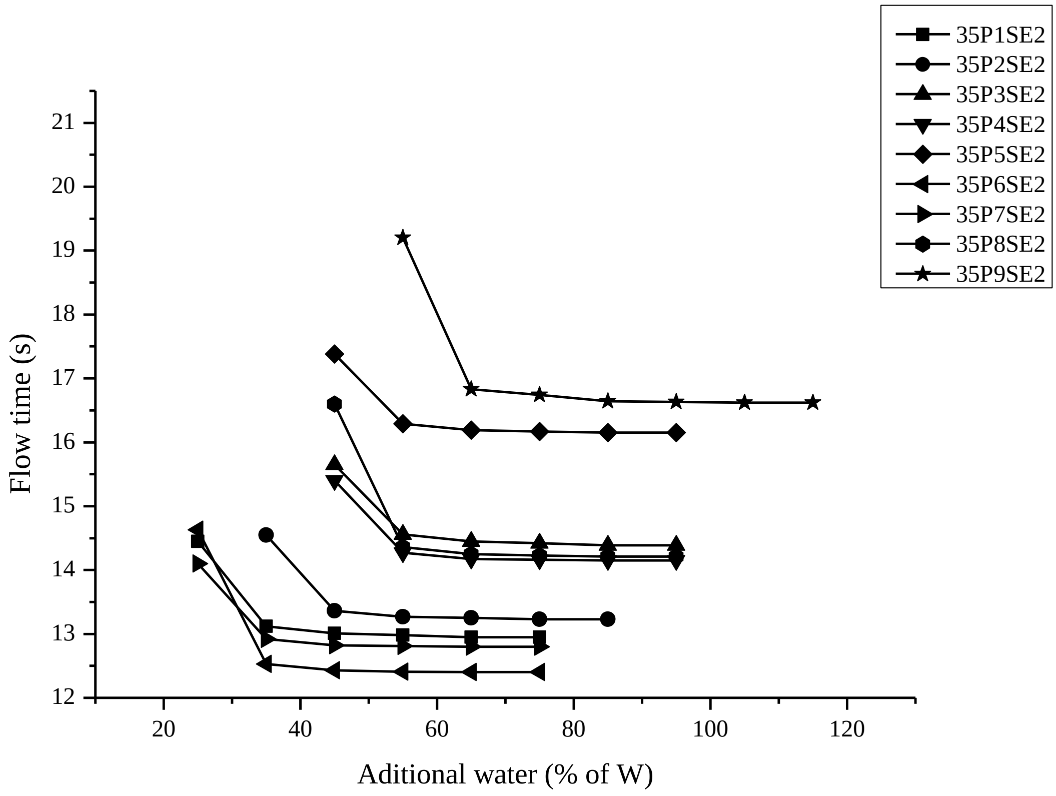

Fig. 3(b): W/B = 0.35

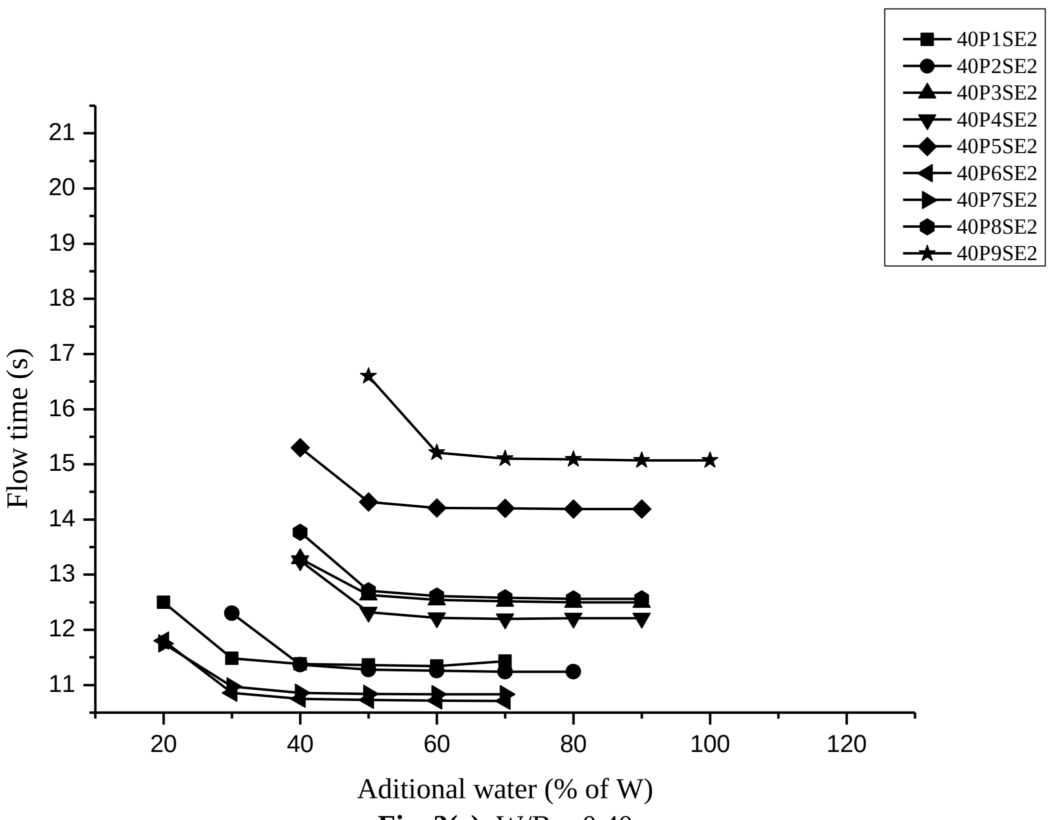

Fig. 3(c): W/B = 0.40

Fig. 3 (a, b, c) Flow time of series 2 binder paste at different percentage increase in water content.

3.3. Water reduction capacity of HRWR

The results of the flow time of series 1 and 2 binder pastes were used to determine the water reduction capacity of the HRWR (Figs. 2 and 3). The flow time data of series 1 binder pastes (Fig. 2) were superimposed on the flow time curve of series 2 binder paste (Fig. 3). This is to determine the increase in the water content required to produce the same flowing ability in the absence of HRWR. Consequently, the water reduction capacity of HRWR was calculated based on the equation formulated by Safiuddin, *et al*. (2011b) as follows:

$$W_R = (W_O - W_{HRWR}) / W_O \times 100 \qquad (1)$$

Where

W_R = water reduction capacity of HRWR (%)

W_{HRWR} = water content for the saturation flow time in the presence of HRWR (kg)

W_O = water content needed for the same flow time without any HRWR (kg)

For example, the flow time of binder paste with 0.30 W/B, containing 5% POFA and 5% PBC was 15.32 s at 1.75% saturation dosage of HRWR. This value is obtained from the flow curve of 30P2SE1 (Fig. 2). In the absence of HRWR, the increase in water required to produce this flow was found from the flow curve of 30P2SE2 (Fig. 3). The value obtained was 56.1%. The water content used for preparing the binder paste with the saturation dosage of HRWR was 1.35 kg. It thus implies that the water required to produce the same flow time can be determined as follows:

W_{HRWR} = 1.35

W_O = (100%+56.1%) = 156.1% of water at the saturation dosage of HRWR

W_O = 1.35 × 156.1/100 = 1.35 × 1.561 = 2.107 kg

The amount of water reduced = $W_O - W_{HRWR}$ = 2.107 – 1.35 = 0.757 kg

Thus,

W_R = 0.757 × 100/2.107 = 35.93 %

Table 5 presents the W_R for various binder pastes. The W_R varied from 26% to 45 %, depending on the saturation dosage of HRWR. It is clear from Table 5 that, higher values of $W_R$were obtained with the increased dosage of HRWR. Nevertheless, the efficiency of HRWR in water reduction depends on the W/B and the content of POFA and PBC. The results showed that HRWR is more effective at lower W/B ratio and higher blended POFA and PBC content (Fig. 5). The lowest WR of 26% was obtained at the W/B of 0.40 and 20% PBC content. In contrast, the WR was significantly higher (45%) at the W/B of 0.3 and 20% POFA and 30% blended POFA and PBC content. This is particularly due to high steric hindrance characteristics of the HRWR molecules at higher surface area and volume of the binder. Similar opinions have been expressed by De Schutter, *et al*., 2008 and Safiuddin, *et al*., 2011c.

This result is in good agreement with the finding of the research carried out by Safiuddin, *et al.* (2011b) on binder paste containing rice husk ash (RHA).

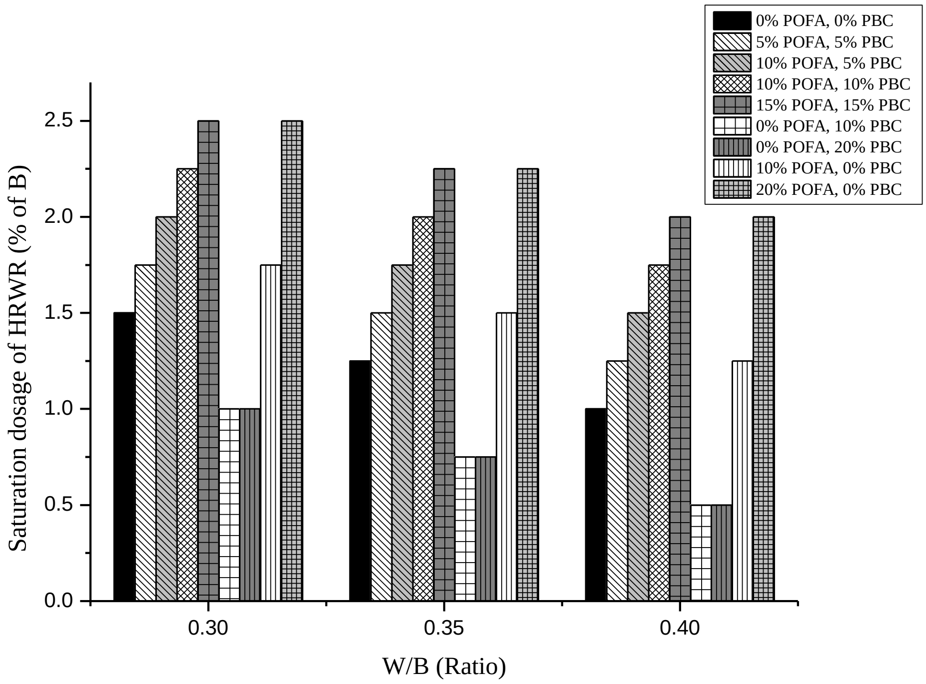

Fig. 4 Effect of the percentage of SCM and W/B on the saturation dosages of HRWR

3.4 Effect of binary and ternary blend of POFA and PBC and the W/B

The pattern of the flow curves presented in Fig. 2 indicated an upward shift in the flow values at an increased content of POFA and blended POFA and PBC and lower W/B. This behaviour is exhibited as a result of increased plastic viscosity of the binder paste. Conversely, the flow curve tends to shift downward at an increased content of PBC, while maintaining the same W/B. This behaviour is due to lower surface area and shear thinning property of the PBC as expressed by Hassan *et al*. (2013). The flow time of the respective binder pastes at saturation dosages of HRWR were derived from the flow curves in Fig. 2 and are presented in Table 5. At higher content of POFA and Blended POFA and PBC, the flowing ability of the binder paste became lower while the saturation flow time value became higher. This is particularly attributed to increased volume fraction and surface area of the binder (Fig. 6). The plastic viscosity of the binder paste increases with an increase in the volume fraction of the binder. Similar findings were reported by De Schutter, *et al*. (2008); Safiuddin, *et al*. (2011b); Struble & Sun, (1995) and Struble, *et al*. (1998). In addition, the surface area of the binder influences the plastic viscosity of the binder paste. Previous research has shown that the higher the surface area of binder, the higher the plastic viscosity (Nehdi, Mindess, & Aïtcin, 1998). In this study, the surface area of the binder used was determined based on Brunauer Emmet and Teller (BET) surface area of cement, POFA and PBC. The computed surface areas of the respective binders are presented in Fig. 7. The surface area of the binder increases with an increase in POFA and blended POFA and PBC content. However, the surface area decreases with an increase in PBC content. Generally, the surface area decreases as the W/B increases. In effect, an increase in the surface area of the binder, decreases the quantity of available free water in the binder pastes thereby, reducing the flowing ability of the binder paste. Safiuddin, *et al*., (2011b) and Safiuddin, *et al*. (2011c) attributed this to the increase in plastic viscosity of the binder paste.

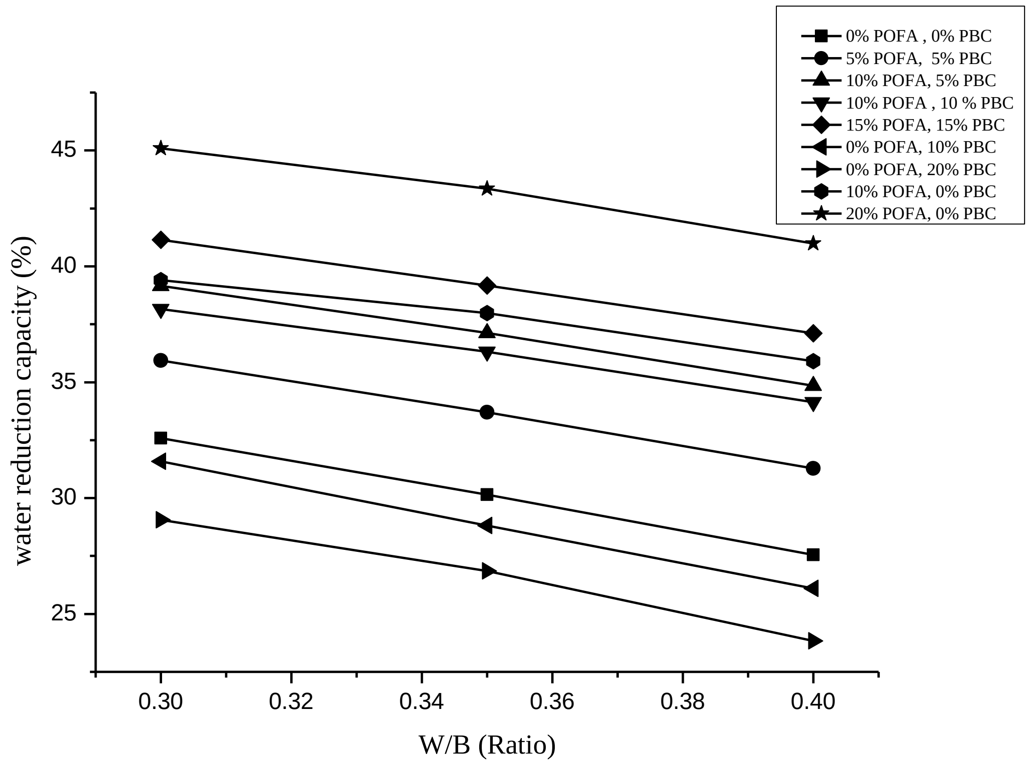

Fig. 5 Effect of percentage of SCM and W/B on the water reduction capacity of HRWR

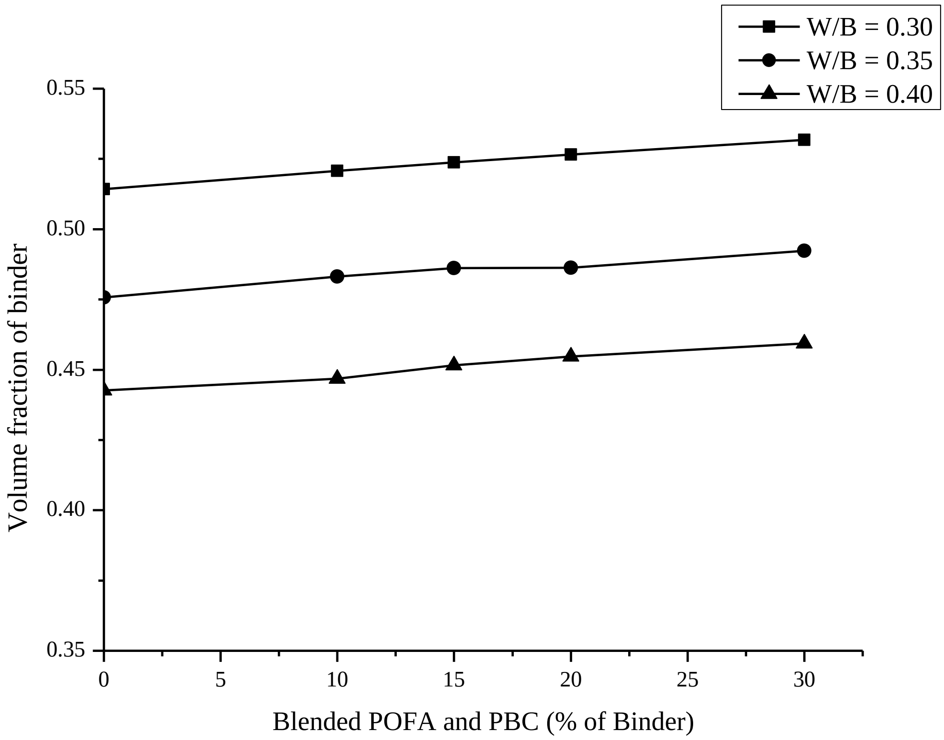

Fig. 6 Effect of blended POFA and PBC content and W/B on the volume fraction of binder in various pastes

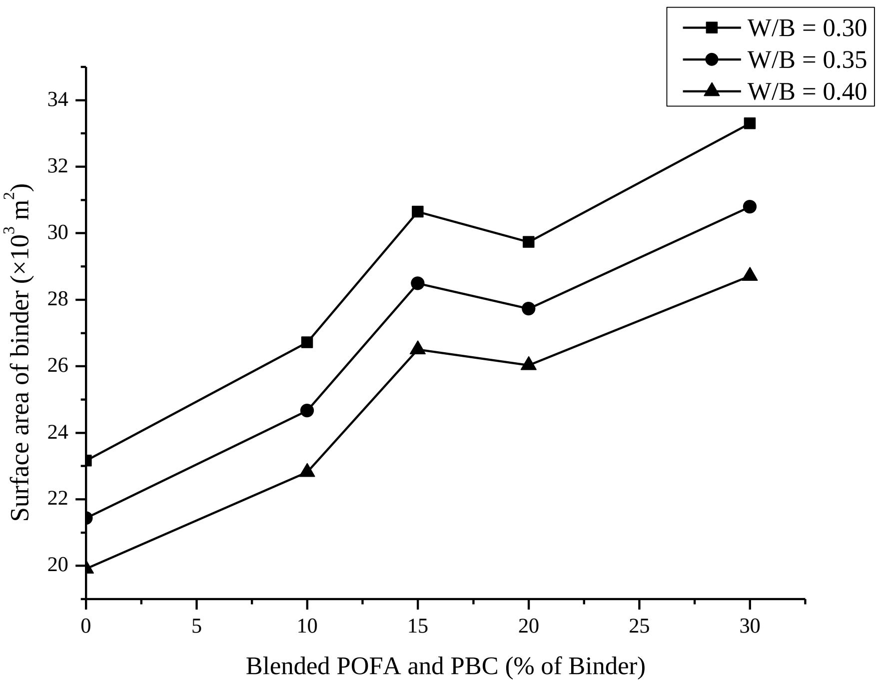

Fig. 7 Effect of blended POFA and PBC content and W/B on the surface area of binder in various pastes

3.5. Water demand of POFA, PBC and POFA/PBC blend

The water demand of POFA, PBC and blended POFA/PBC contents were determined based on the flow time results presented in Fig. 3 and the consistency results presented in Table 6. Both approaches provided the information on the amount of additional water content required for the binder pastes with binary and a ternary blend of OPC, POFA and PBC and the paste without any SCM to produce the same flow rates as those of the saturation dosage of HRWR. The water demand of the respective SCM was calculated using equation 2 from the paste saturation flow time and equation 3 from standard consistency test.

$$W_D=W_{SCM}-W_{OPC} \quad (2)$$

Where:

WD = water demand of SCM

WOPC = percentage increase in water content required for the binder paste without SCM

WSCM = percentage increase in water content required for the binder paste with SCM

As an illustration, the flow time at a saturation dosage of HRWR for series 1 binder paste with W/B of 0.30 and 10% blended POFA and PBC (30P2SE1) was obtained from Fig. 2 (a) as 15.32 seconds. The additional water content required to achieve the same flow time in the absence of HRWR was determined from Figure 3(a) to be 56.10%. The additional water content required for the binder paste with 0.30 W/B and 0% blended POFA and PBC to achieve the required saturation flow time without HRWR was 48.30%. Thus the water demand of the 10% blended POFA and PBC can be calculated as;

WD = 56.10% - 48.30% = 7.8%.

Table 5 presents the saturation flow time and the corresponding water demand required to achieve the flow time for the binary and ternary blend of OPC, POFA and PBC. It can be observed from Table 5 that for a binary blend of OPC and PBC, there is a decrease in the water demand as the percentage of PBC increase. Hence, negative values of -2.10% and -6.30% were recorded for 10 and 20% of PBC. This behaviour is due to the water reduction characteristics of the PBC as reported by Ismail *et al*., 2013. On the other hand, for a binary blend of OPC and POFA, there is an increase in the water demand as the percentage of POFA increase. Consequently, the values 17.22% and 33.81% were recorded for 10 and 20 % of POFA respectively. This result is due to high surface area and water absorption characteristics of POFA as reported by Hassan, *et al*. (2013) and Ismail, *et al*. (2013). Furthermore, the water demand of the ternary blend of OPC, POFA and PBC increases with an increase in the percentage of blended POFA and PBC. The water demand was observed to be higher at lower W/B due to the higher quantity of the blended SCM. Notwithstanding, the water demand of the blended SCM varies from -6.70% to 33.81%. This depends on the percentage replacement and W/B. The highest water demand of 33.81% was observed for 20% POFA content in the binder paste with W/B of 0.30. While the lowest value of -6.70% was observed for 20% PBC content in the binder paste with W/B of 0.40. The reduced water demand of PBC is as a result of the agglomeration of the particles during calcination, high content of glassy particles and non-porous nature of the particles. On the other hand, the higher water demand of POFA is associated with high surface area, high content of un-burn carbon, porous and irregular particle structure as reported by Hassan, *et al*. (2013).

3.6. Appropriate replacement level of POFA and PBC

The result of this study shows that the additions of POFA and PBC in binary and ternary blends have a significant effect on the flowing ability of the binder paste. The flowing ability of the binder paste decreases with increase in POFA content due to the increase in water demand. It was observed that POFA has a relatively high water demand at a percentage replacement of 20% (30P9P20:0), which is an indication that at higher replacement levels, the demand will be much greater. In contrast, the flowing ability of the binder paste increases with increase in PBC content due to the decrease in water demand. It was observed that PBC has a very low water demand at a percentage replacement of 20% (30P7P0:20). Generally, in all the binder paste containing binary and ternary blends of POFA and PBC, the water demand was lower than the water reduction capacity of the HRWR at saturation dosages. These therefore mean that a blend of POFA and PBC will have a positive impact on the flowing abilities of the binder pastes and the parent concrete. Furthermore, in all cases, the saturation dosages of the HRWR were below 3%, which can be considered suitable for self-compacting concrete as reported by Kwan (2000). Also, it was reported by Kwan (2000) that a HRWR saturation dosage above 3% is mostly associated with delay hydration and setting time. Consequently, a blended POFA and PBC of up 30% (15%POFA and 15%PBC) with a HRWR saturation dosage of ≤ 2.5% is considered suitable for the production of self-consolidating paste and concrete with W/B ≤ 3.0 and up 0.40.

3.7. Significance of the flowing ability test on self-consolidating binder paste

Flowing ability test on binder paste is an essential tool in the mix design process of self-consolidating concrete. It facilitates the evaluation of the optimum content of the key constituent materials such as Cement, SCM and HRWR in the production of self-consolidating concrete. The paste optimisation process reduces the volume of laboratory work as well as reducingmaterial wastage associated with bulky trial mixes. Furthermore, it provides a sound base for the evaluation of the potency and suitability of SCM and the efficacy of HRWR in the production of SCC and SCHPC.

In this study, the result of the flowing ability was used to evaluate the appropriate replacement percentages of blended POFA and PBC, based on the saturation dosage and water reduction capacity of the HRWR and the water demand of binary and ternary blend of OPC, POFA and PBC. The result can therefore be used to proportion the materials for the parent Self-consolidating concrete.

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4.0 Conclusions

The current study carried out flowing ability test on self-consolidating binder paste in order to evaluate the appropriate replacement percentages of blended POFA and PBC. The evaluation was based on the saturation dosage and water reduction capacity of the HRWR and the water demand of binary and ternary blend of OPC, POFA and PBC. The findings revealed that:

1. The flowing ability of the binder paste increases as a result of the decrease in flow time at higher dosages of HRWR. This is mainly attributed to the liquefying and dispersing action of HRWR.
2. The flow time of the binder pastes increases with decrease in W/B ratio and higher content of only POFA and blended POFA/PBC. This is particularly due to higher plastic viscosity, resulting from very high volume fraction and surface area of the binder.
3. Lower flow time of the binder pastes was observed at lower W/B and higher content of PBC. This is particularly due to lower plastic viscosity, resulting from lower volume fraction and the surface area of the binder.
4. The binder paste with lower W/B and higher content of POFA and blended POFA and PBC, requires higher dosages of HRWR to attain saturation flow. This is attributed to the increase in flocculation forces as a result of increase in the volume fraction of binder.
5. The water reduction capacity of HRWR increases with decrease in the W/B at higher content of POFA and blended POFA/PBC. This could be attributed to higher steric hindrance characteristics of the HRWR at a higher volume fraction of binder.

6. The water demand required to achieve saturation flow increases with an increase in the content of POFA and Blended POFA and PBC. This is due to high surface area of POFA which is associated with high content of un-burn carbon, porous and irregular particle structure.
7. A blended POFA and PBC of up 30% (15%POFA and 15%PBC) is considered suitable for the production of self-consolidating paste and concrete with W/B ≤ 3.0.
8. The appropriate content of blended POFA/PBC and the dosage of HRWR for a particular SCC or SCHPC can be selected based on the flowing ability of its paste component. As such, it is one of the key operations in the mix design of SCC or SCHPC.

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