Effect of Ternary Blended Binder on Mechanical and Microstructural Properties Self-consolidating Cement Mortar

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ABSTRACT

In this study, palm oil fuel ash (POFA) an agro-based waste material and Pulverised burnt clay (PBC) an industrial based waste material both with pozzolanic properties were used to evaluate the strength and the microstructural characteristics of self-consolidating cement mortar (SCCM). Ordinary Portland cement (OPC) and water-binder ratio (W/B) of 0.30, 035 and 0.40 were used to produce fifteen (15) different cement mortar mixes with 0, 10, 15, 20 and 30% of blended POFA/PBC as Partial replacements of the OPC. The effects of the respective W/B and the blended percentages of POFA and PBC on the compressive strength and the microstructure of the various mortar specimens were investigated. Furthermore, the effect of the microstructural characteristics on the strength development pattern was analysed and reported. It was observed that the inclusion of various blends POFA/PBC resulted in a refinement of the microstructure and consequently lead to a significant increase in compressive strength, particularly at ages beyond 28 days. Hence, SCCM of desirable characteristics can be produced when a blend of POFA and PBC is used to replace up to 30% of OPC.

Keywords: *Cement mortar; Microstructure; Strength; Self-consolidating;Ternary Blended Powder.*

Introduction

Self-consolidating concrete (SCC) is usually considered to be a broad range of mixtures in which the fresh and hardened properties are selected to suit a specific application. As with all concrete, the hardened properties of SCC mixtures are the dominant criteria for success [1].

Generally, SCC is often looked at as a two-phased material; either as a coarse aggregate in a matrix of mortar or as an aggregate skeleton in a matrix of paste. Nonetheless, in which ever way it is looked at, the mortar component plays as significant role on the properties of the parent concrete in both fresh and hardened state [2]. In addition, the paste component plays a key role of shaping the internal microstructure of both the mortar and concrete.

SCC is usually associated with many technical and economic advantages. Notwithstanding, its cost could be 23–38% higher than normal concrete [3]. Supplementary cementing materials (SCMs) and mineral admixtures such as fly ash, palm oil fuel ash, pulverised burnt clay, limestone and blast-furnace slag could be used to reduce the cost of SCC. Furthermore, it was reported that the cost of producing SCC with fly ash varies between 10 – 17% higher than that of normal concrete, depending on the quantity of fly ash used [4]. Also, [5] reported that the cost difference is around 15%. Nonetheless, recent research has discovered that by eliminating the cost of vibration work, reduction of labour, reduction in construction time and the use of inexpensive waste materials in can reduce the overall cost of SCC work by 24.8% in comparison with NC [6].

The use of such admixtures can also increase the slump of the concrete mix as well as improve the mechanical, deformation and durability characteristics of concrete. Interestingly, the incorporation of these SCMs in binary, ternary and quaternary blends tend to produce self-consolidating systems that usually exhibit complex hydration mechanisms. These complex behaviours are primary attributed to the particle size, shape morphology and the internal microstructure of the SCMs [7].

The present work focused on the use of blended palm oil fuel ash and pulverised burnt clay bricks as SCMs to produce self-consolidating cement mortar. The mechanical and the microstructure characteristic of the mortar were investigated.

2. Materials and methods

2.1 Constituent materials

In this study, the cement used was type I Portland cement conforming to ASTM C 150 [8]. Its specific surface area was 5.067 m^2/g determined by Brunauer Emmet and Teller (BET) method. The supplementary cementing materials (SCMs) used were POFA and PBC.POFA has a specific gravity of 2.42 and that of PBC was 2.69 while the BET surface areas were 23.751 and 2.979 m^2/g, respectively. 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 [9] class F polycarboxylic-based HRWR. It is amber in colour and has a specific gravity of 1.10 at 25 ^{O}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.

Table 1 Chemical properties of the respective binders

Oxide composition	Supplementary cementing material		
	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_2O5	-	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

2.2 Mix proportion and mortar designation

In this study, a total of 15 different mortar mixtures was prepared. The mortars were categorised into 3 groups based on the water to binder ratio (W/B) of 0.30, 0.35 and 0.40 (Table3). Each group consisted of 0, 10, 15, 20 and 30% blend of POFA and PBC. These mixtures were based on the mixture proportion of the corresponding SCC. 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 point.

The respective mortars designation was based on the W/B and the proportions of the SCCM as present in the parent SCCs. For instance, ‘‘30M1P0:0’’ designation was used for mortar prepared with a W/B ratio of 0.3, 0% POFA and 0% PBC, while “40M5P5:5” represents the mortar prepared with a W/B ratio of 0.40, 5% POFA and 5% PBC. The mix proportion and the designation of the various mortars are presented inTable 3.

Table 2 Physical properties of the constituent materials

Material	Properties
Fine aggregate	Specific gravity on saturated surface dry basis: 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): 5.067m²/g Median particle size: 15.0
Palm oil fuel ash (POFA)	Specific gravity: 2.42 Percentage passing 45-μm wet sieve: 98.4% Specific surface area (BET): 23.7514m²/g Median particle size: 11.0
Pulverised burnt clay brick (PBC)	Specific gravity: 2.69 Percentage passing 45-μm wet sieve: 96.4% Specific surface area (BET): 2.9791m²/g Median particle size: 10.0
High range water reducer (HRWR)	Specific gravity: 1.10 pH value: 8 Solid content: 42%

2.3 Mixing and casting

The respective mortars were prepared using a medium sized revolving type mechanical mixer conforming to ASTM C 305 [10] specification. The casting operation was carried out immediately after the mixing process. Mortar cubes of size 50 x 50 x 50 mm were cast for the determination of compressive strength and scanning electron microscopy after 3, 7, 28 and 90 days.

Aftercasting, the test specimens were left in the casting room for 24 h at a temperature of about 20 ^{O}C ± 0.5, in 100% relative humidity. The specimens were removed from mould after 24 h, and then immersed in water-curing tank until the required time of the test.

Table 3. Mixture proportion and designation of the respective mortars

Mortar Designation	Percentage Replacement		W/B	Fine aggregate (kg)	Cement (kg)	POFA (kg)	PBC (kg)	Water (kg)	HRWR dosage (%B)
	POFA (%)	PBC (%)							
30M1	0	0	0.30	4.77	3.14	0.00	0.00	1.02	1.50
30M2	5	5	0.30	4.77	2.79	0.15	0.15	1.01	1.75
30M3	10	5	0.30	4.77	2.61	0.31	0.15	1.00	2.00
30M4	10	10	0.30	4.77	2.45	0.31	0.31	1.00	2.25
30M5	15	15	0.30	4.77	2.12	0.45	0.45	0.99	2.50
35M1	0	0	0.35	4.77	2.90	0.00	0.00	1.10	1.25
35M2	5	5	0.35	4.77	2.58	0.14	0.14	1.09	1.50
35M3	10	5	0.35	4.77	2.42	0.28	0.14	1.08	1.75
35M4	10	10	0.35	4.77	2.27	0.28	0.28	1.07	2.00
35M5	15	15	0.35	4.77	1.96	0.42	0.42	1.06	2.25
40M1	0	0	0.40	4.77	2.70	0.00	0.00	1.16	1.00
40M2	5	5	0.40	4.77	2.4	0.13	0.13	1.15	1.25
40M3	10	5	0.40	4.77	2.25	0.27	0.13	1.14	1.50
40M4	10	10	0.40	4.77	2.11	0.26	0.26	1.14	1.75
40M5	15	15	0.40	4.77	1.83	0.39	0.39	1.13	2.00

2.4 Microstructure

This phase of the study is necessary because almost all short and long time properties of cementitious systems depend on the microstructure of the hardened paste matrix. The crystallographic properties were investigated by means of scanning electron microscopy (SEM).The SEM device used was SUPRA FESEM versatile ultra-high resolution with a variable pressure solution, equipped with an energy dispersive X-ray analyser (EDX).The samples for the investigation were obtained immediately after the specimens were crushed for compressive strength determination. The samples were immediately immersed in containers containing acetone. The samples were then oven dried for 24 h at 105 ^{O}C to stop the hydration process.

3. Results and discussion

3.1 Compressive strength determination

The results of the compressive strengths of the respective SCCM are as shown in Figs. 1 to 3. The respective strength values were determined for a period of 1 year. The gain in compressive strength continued to occur until the age of 365 days where highest strength values were achieved for all SCCM systems due to the enhancement of the hydration process in the presence of blended POFA and PBC. Similar results were reported by [11]. However, rapid and the largest strength development occurred between 3 and 28 days, as can be seen from Figs. 1 to 3. Safiuddin, et al., [12] reported the similar behaviour for SCHPC incorporating RHA.

The compressive strength of the respective SCCM was increased significantly at lower W/B as can be seen from Figs. 1 to 3. This increase in strength could be attributed to the increased densification of the paste matrix. [13, 14] reported that the increase in compressive strength of concrete or mortar is directly related to the matrix density and porosity of the system. Thus, in the present study, owing to the lower W/B employed (0.3 to 0.4), there was a reduction in the total porosity of the bulk mortar matrixas can be seen in Fig. Consequently, it can be inferred that the microstructure of mortar was improved in both bulk paste matrix and interfacial transition zone. Similar characteristics were also reported [12]. Furthermore, the binder content became higher at lower W/B. Hence, it was concluded that the increased binder content resulted in improved physical packing of aggregates and higher production of calcium silicate hydrate (C-S-H) which consequently resulted to higher compressive strength.

The addition of blend of POFA and PBC significantly increased the compressive strength of the respective SCCM at the ages of 7, 28, 90 and 365 days, as can be seen from Figs. 1 to 3. The improvement of compressive strength could be attributed to the "micro-filling ability" and "pozzolanic activity" of the SCMs. With smaller particle sizes in comparison to OPC (Table 2), the blended POFA/PBC can fill the micro-voids within the cement particles. Also, both the POFA and PBC particles readily react with water and calcium hydroxide from cement hydration to produce additional calcium silicate hydrate or CSH [15, 16]. The additional C-S-H increases the compressive strength of concrete. It reduces the porosity of concrete by filling the capillary pores, thereby improving the microstructure of the mortar's bulk paste matrix and transition zone resulting in increased compressive strength.

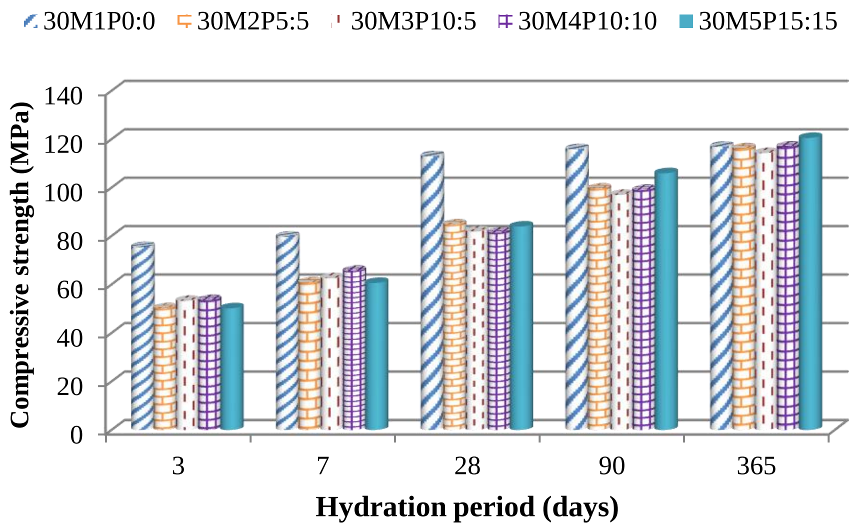


Fig. 1 Compressive strength development of various SCCM (W/B = 0.30)

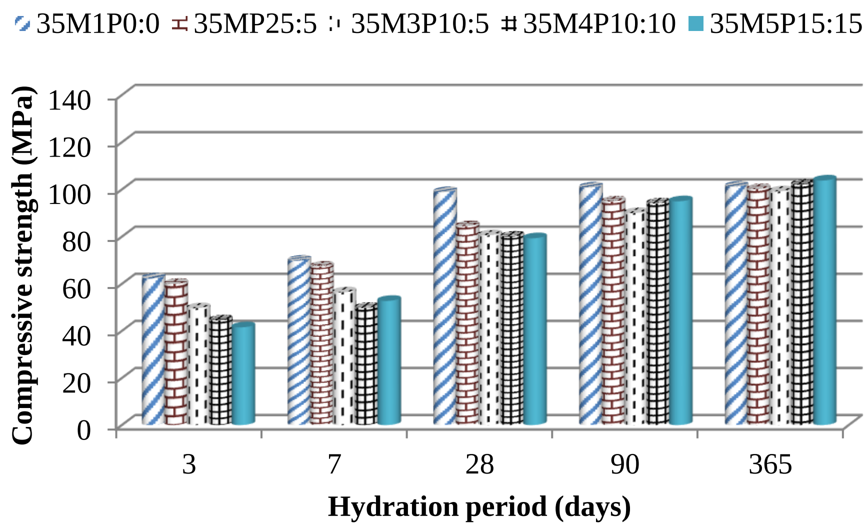


Fig. 2 Compressive strength development of various SCCM (W/B = 0.35)

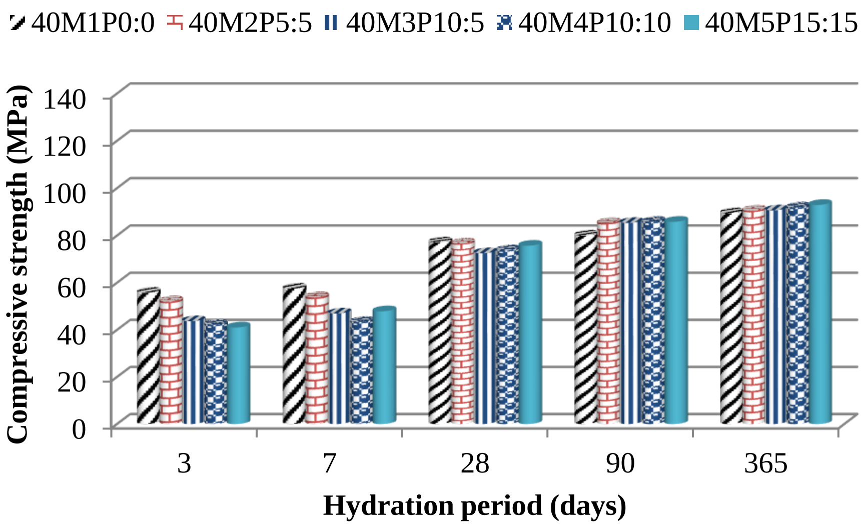


Fig. 3 Compressive strength development of various SCCM (W/B = 0.40)

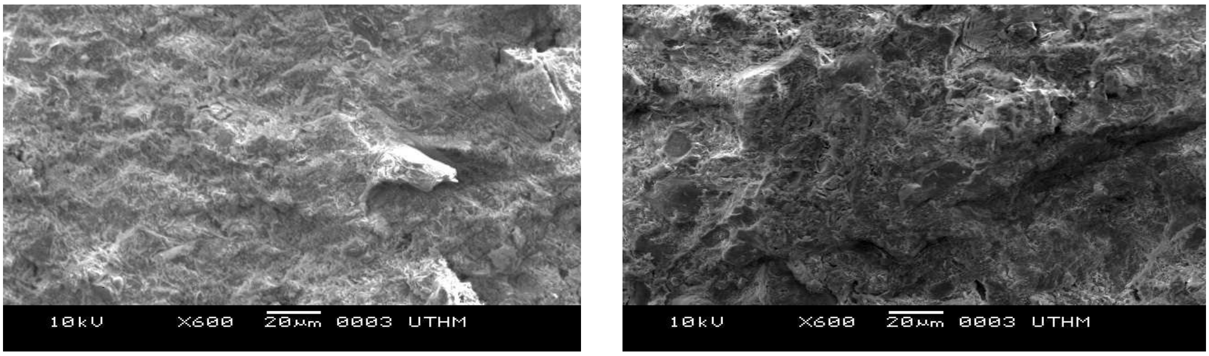
3.2 Microstructural characteristics

Scanning electron microscopy (SEM) images of the paste component of the SCCM are presented if Figs. 4 to 7. The mortars with 0 and 30% blend of POFA and PBC were selected to observe the microstructure. This is because 30% blend of POFA and PBC produced a comparable strength to the control at 28days. Also, it produced the highest level of mechanical strength at 90 and 365 days.

The inclusion of the blend of POFA and PBC improved the microstructure of concrete at both early and later ages. Figs. 4 and 5shows the SEM images of 30M1P0:0 and 30M5P15:15 to establish a comparison between the microstructure of SCHCs with and without POFA at the early ages of 3 and 7 days (for the EDX, refer to appendix). Both 30M1P0:0 and 30M5P15:15 were more porous at 3 days than at 7 days respectively, which are obviously seen in Figs. 2 and 3. Nonetheless, the microstructure of the concrete containing 30% of the blended binder was relatively less porous in comparison with the control specimen.

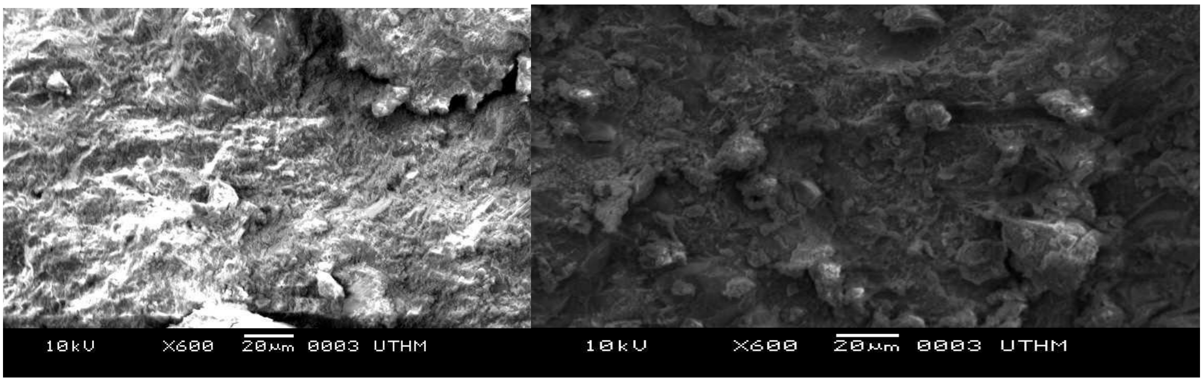
Interestingly, the microstructure of the respective SCCM changed as the curing age progresses. Figs. 7.3 and 7.5 show the SEM images of the respective concretes 30M1P0:0 and 30M5P15:15) at 28 and 90 days respectively. This was aimed at establishing a comparative assessment between the microstructures at older ages of the SCCM with and without the blend of POFA and PBC. C-S-H has been acknowledged to be the predominant product phase at ages higher than 28 days for all concretes [13]. A closer observation indicated that there were no needle-like ettringite products in the SEM of all the concretes at these ages. This is because ettringite is generally formed in the early ages (≤ 7 days) of hydration and disappeared as the cement hydration continues beyond 7 days [13].

Generally, all the mortars containing the blend of POFA and PBC were less porous than the non-POFA/PBC concretes, as understood from the SEMs presented in Figs. 4 to 7. This is an indication of the fact that a blend of POFA and PBC contributed to the densification of the microstructure of the respective SCCM at later ages due to its micro-filling ability and pozzolanic activity. This improvement of the concrete microstructure occurred in the bulk paste matrix as well as the interfacial transition zone. Consequently, the porosity was substantially reduced in the presence of 30% blend of POFA and PBC, as have been observed in Figs. 6 (b) and 7 (b). Similar effects were reported by Yu & Brouwers [16], Salam, et al., [17] and Heikal, et al., [11] in the case of high-strength and high performance paste and concretes containing POFA, PBC and β-hemihydrate produced gypsum.



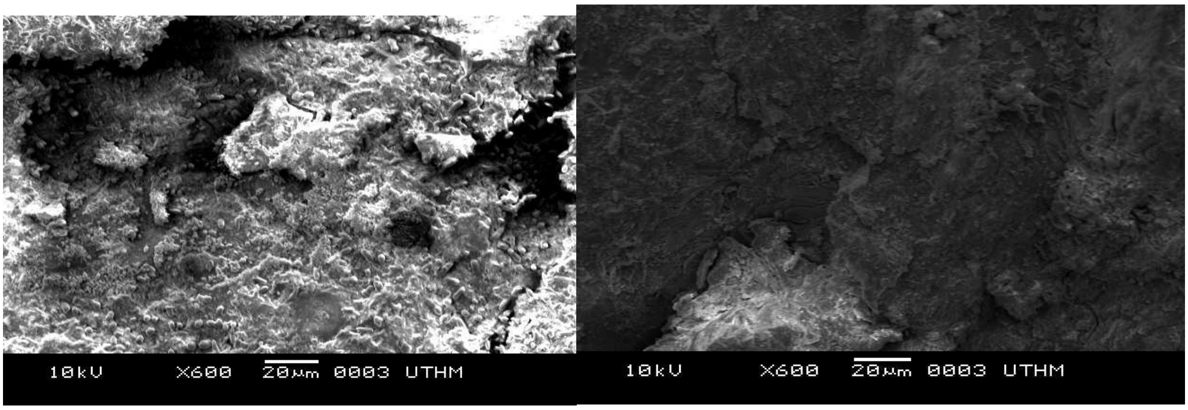
(a) 30M1P0:0 (3 days) (b) 30M5P15:15 (3 days)

Fig. 4 Microstructure of 0% and 30% blended SCHPC at 3 days



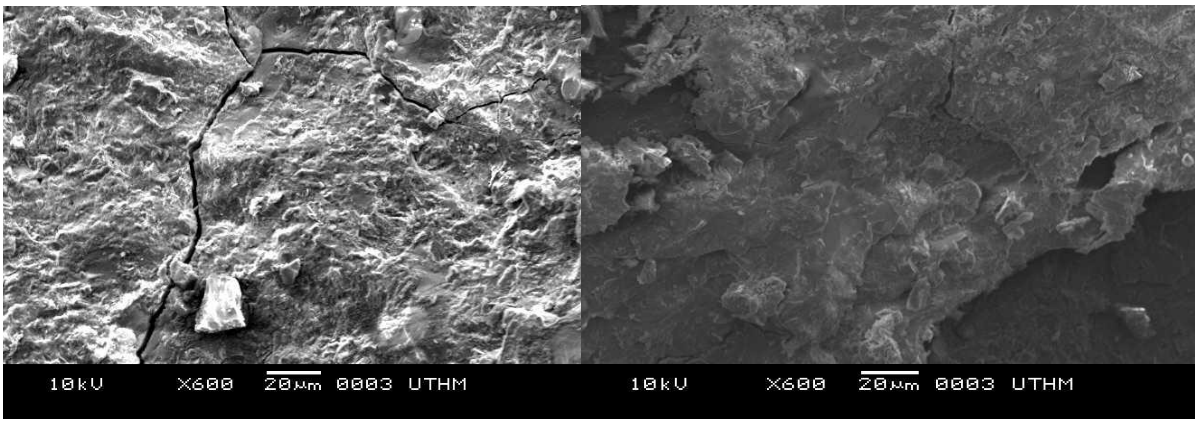
(a) 30M1P0:0 (7 days) (b) 30M5P15:15 (7 days)

Fig. 5 Microstructure of 0% and 30% blended SCHPC at 7 days



(a) 30M1P0:0 (28 days) (b) 30M5P15:15 (28 days)

Fig. 6 Microstructure of 0% and 30% blended SCHPC at 28 days



(a) 30M1P0:0 (90 days) (b) 30M5P15:15 (90 days)

Fig. 7 Microstructure of 0% and 30% blended SCHPC at 90 days

4.0 Conclusions

From the results of the study carried out, the following conclusions can be drawn:

1. The compressive strength of the respective SCCM increases with the increase in the hydration period up 365 days.
2. The compressive strength decreases when the W/B was increased from 0.30 to 0.40
3. The compressive strength increases with an increase in the blend of POFA and PBC content up to 30%.
4. Generally, SCCM containing 30% blended POFA and PBC exhibited higher compressive strength at 365 days for W/B of 0.30, 0.35 and 0.40 respectively.
5. The presence of the Blend of POFA and PBC as pozzolanic materials resulted in the densification of the microstructure due to the formation of secondary hydration products as shown in the micrograph, and consequently enhances the compressive strength.

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