The Effect of Blended Palm Oil Fuel Ash and Pulverised Burnt Clay on the Relationship between Hardened Properties of Self-Consolidating High Performance Concrete

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***Abstract*— The application of palm oil fuel ash and pulverized burnt clay in self-consolidating concrete has been acknowledged to have significant influence on the fresh properties of the concrete. In contrast, the effect on the hardened properties has not yet been established. In this study, a blend of Palm oil fuel ash (POFA) and pulverized burnt clay (PBC) was used as partial replacement of Ordinary Portland cement (OPC) to produce self-consolidating high performance concrete (SCHPC). Fifteen different mixes were prepared with varying percentages of blended POFA/PBC, high range water reducing admixture (HRWR) and water to binder ratio (W/B) ranging from 0.30-0.40. Three key hardened properties were investigated. The mechanical properties were investigated based on the compressive strength, tensile strength, flexural strength and ultrasonic pulse velocity. The deformation characteristics were investigated with respect to drying shrinkage and modulus of elasticity. The durability properties were investigated based on the water permeability, total porosity, rapid chloride ion penetration and electrical resistivity. A comparative analysis was carried out on the results based on the correlations established among the hardened properties of the respective mixes. The research findings revealed strong correlations between most of the hardened properties of the respective SCHPC.**

Keywords- Blended; Concrete; High Performance; Palm oil fuel ash; Pulverised burnt clay; Self-consolidating

I. INTRODUCTION

One of the basic solutions towards achieving improved concrete characteristics both in the fresh and hardened state is the employment of self-consolidating concrete (SCC) or self-consolidating high performance concrete (SCHPC). This is because it tends to transform the concreting operation by completely eliminating the need for vibration and allows the concrete to be consolidated through sections with congested reinforcement under its self-weight without any segregation [1, 2].

The three basic categories of hardened properties of SCHPC are influenced by the W/B, the quantity of SCM, volume fraction of paste, volume fraction of fine and coarse aggregates and the interfacial bond between the aggregates and the bulk paste matrix [3-5]. The mechanical strengths, deformation characteristics and the durability properties of SCHPC may be alternately influenced, either directly or indirectly by the aforementioned factors. Therefore, evaluation of the correlation between these properties will be the key to successful design, production and application of SCHPC.

The evaluation of the correlations between mechanical strengths and deformation characteristics, and the mechanical strengths and durability properties of the concretes were carried out.

II. MATERIALS AND METHODS

A. Materials

The materials used in this research work include; normal ASTM C150 [6] type I Portland cement (OPC) with a specific gravity of 3.15, BET surface area of 5.067 m2/g, Palm oil fuel ash and pulverized burnt clay brick with a specific gravity of 2.42 and 2.69 and BET surface area of 23.751 and 2.979 m2/g respectively. A well graded pit sand having a fineness modulus of 2.4, a specific gravity of 2.55, bulk density of 1682 kg/m3 and absorption value of 1.8% was used. The coarse aggregate used was crushed aggregate with a specific gravity of 2.56, bulk density of 1609 kg/m3 and absorption value of 1.6%.

A polycarboxylic-based polymer was used as the high range water reducer (HRWR). The HRWR is amber in color and has a specific gravity of 1.10 at 25oC with a pH value of 8. The mixing water used was normal tap water.

B. Mix proportions

Fifteen different mixes of SCHPC were prepared using a blend of POFA and PBC at a replacement levels ranging between 0-30% (0%/0%, 5%/5%, 10%/5%, 10%/10%, and 15%/15% of POFA/PBC respectively) as partial replacement of OPC. The W/B used was 0.30, 0.35 and 0.40 respectively. The W/B was selected based on [7] guidelines. The water and the cement contents were determined based on the selected W/B using a developed rational mix design procedure. Saturation dosages of HRWR were determined for each of the respective mixes to achieve slump flow values in the range of

650-800mm based on [8] guidelines. The designation of the mixes was based on the on the selected W/B, and the percentage of the blended POFA/PBC. For example, 30C1P0:0 is a designation for SCHPC mix with W/B of 0.30, blended POFA and PBC content of 0%/0%. The details of the mix proportions of the various SCHPC mixes are presented in Table1.

Table 1 Details of the mix proportions for various ternary blended SCHPC

Concrete Numenclature	POFA (% of B)	PBC (% of B)	W/B Ratio	Coarse aggregate	Fine aggregate	Cement (kg)	POFA (kg)	PBC (kg)	Water (kg)	HRWR (% of B)
30C1P0:0	0	0	0.30	811.20	811.20	532.99	0.00	0.00	181.27	1.50
30C2P5:5	5	5	0.30	811.20	811.20	473.93	26.33	26.33	178.64	1.75
30C3P10:5	10	5	0.30	811.20	811.20	444.26	52.27	26.13	176.74	2.00
30C410:10	10	10	0.30	811.20	811.20	416.28	52.04	52.04	175.32	2.25
30C5P15:15	15	15	0.30	811.20	811.20	359.98	77.14	77.14	172.82	2.50
35C1P0:0	0	0	0.35	811.20	811.20	493.06	0.00	0.00	195.00	1.25
35C2P5:5	5	5	0.35	811.20	811.20	438.83	24.38	24.83	192.42	1.50
35C3P10:5	10	5	0.35	811.20	811.20	411.52	48.41	24.21	190.54	1.75
35C4P10:10	10	10	0.35	811.20	811.20	385.78	48.22	48.22	189.19	2.00
35C5P15:15	15	15	0.35	811.20	811.20	333.89	71.55	71.55	186.73	2.25
40C1P0:0	0	0	0.40	811.20	811.20	458.70	0.00	0.00	206.82	1.00
40C2P5:5	5	5	0.40	811.20	811.20	408.56	22.70	22.70	204.29	1.25
40C3P10:5	10	5	0.40	811.20	811.20	383.32	45.10	22.55	202.47	1.50
40C4P10:10	10	10	0.40	811.20	811.20	359.45	44.93	44.93	201.16	1.75
40C5P15:15	15	15	0.40	811.20	811.20	310.91	66.62	66.62	198.51	2.00

A. *Preparation of concrete*

The fresh concrete mixes were prepared with the revolving type, pan concrete mixer with a nominal capacity of 0.015m3 as specified by [9]. First, the coarse and fine aggregates were first blended and charged into the concrete mixer with one-quarter of the adjusted water required for mixing for 180 seconds. The mixer was stopped and allowed to rest for 180 seconds so as to give room for the air-dried aggregates to absorb water required for saturation. This was done in order to avoid the absorption of the HRWR by the aggregates. Thereafter, the cementing materials (OPC with and without blended POFA and PBC) were charged in the mixer. Immediately, the mixer was restarted and the mixing was continued for 120 seconds with the addition of the second and the third quarter of the mixing water. Then the HRWR was dispersed in the fourth quarter of the mixing water and then added to the concrete mix and the mixing was continued for another 180 seconds.

B. *Test on the hardened properties*

After the required fresh properties test were successfully conducted on the fresh concrete, 100x100 mm cubes, 100x200 mm cylinders and 100x500 mm prisms were cast. The specimens were de-molded and cured in the water tank until the required hydration period. The cube specimens were used for the determination of the compressive strength and ultrasonic pulse velocity. The cylindrical specimens were used for the determination of the splitting tensile strength, modulus of elasticity, water absorption and porosity. Prismatic specimens were used to determine the flexural strength of the hardened concrete. The specimens for the water absorption and porosity were 100x50 mm disc which were cut from the 100x200 mm cylinders.

The respective hardened properties were determined after the ages of 28 and 90 days. The compressive strength was determined in accordance with [10] specification. The splitting tensile strength test was carried out according to [11]. the flexural strength was determined based on [12] guideline. The procedure specified by [13] was used to determine the modulus of elasticity of the concrete. The ultrasonic pulse velocity was determined in line with [14]. The water absorption and porosity were determined in accordance with [15] specification. The rapid chloride ion penetration was determined based on [16] specification and the electrical resistivity of the respective hardened concretes was determined in accordance with [17].

III. RESULTS AND DISCUSSION

A. *Correlation between compressive strength and tensile strength*

The splitting tensile strength (fsp) of the respective SCHPC had a strong correlation with the square root of the compressive strength (√f'c). The correlation was linear and positive as shown in figure 1. The correlation was determined for compressive strength in the range of 53.44 MPa to 94.95 MPa and splitting tensile strength in the range of 4.56 MPa to 6.22 MPa respectively. The correlation coefficient was found to be +0.9135, which is an indication of a strong positive relationship. Similar relationships were reported by [18] and [19] for high strength concretes containing SF and POFA. This sort of relationship could be attributed to the similarity in the development pattern of compressive and splitting tensile strength. The splitting tensile strengths of the respective SCHPC were in the range of 6 – 9 % of the compressive strength values. [20] specified a range of 7 – 17 %, depending on the quality of the concrete. [21] stipulated that the relationship between the splitting tensile and compressive strength of normal concrete can be expressed as fsp = 0.556√f'c. In this study, the relationship was found to be fsp = 0.6901√f'c, which was about 24% greater than that of normal concrete. This could be attributed to the enhancement of both the splitting tensile strength and the compressive strength of the SCHPC due to the pozzolanic action of both POFA and PBC.

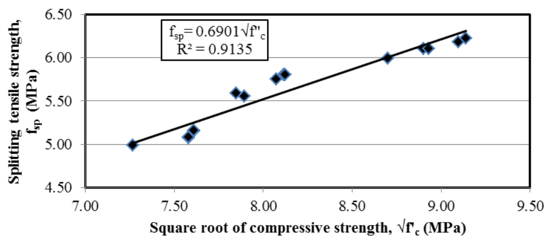

Figure 1. Correlation between compressive strength and tensile strength

B. *Correlation between compressive strength and flexural strengthEquations*

The flexural strength (fr) and the square root of the compressive strength (√f'c) had a strong and positive linear correlation as shown in figure 2. The relationship was determined for compressive strength values ranging between 53.44 MPa to 94.95 MPa and flexural strength in the range of 4.59 MPa to 9.85 MPa respectively. The correlation coefficient was found to be +0.9007, which is an indication of an excellent relationship. This excellent relationship could be attributed to the same response to W/B and the blended binder content as previously discussed. [21] specified a relationship between compressive and flexural strengths as fr = 0.622√f'c for NVC. In this study, the relationship was found to be fr = 0.9998√f'c for the respective SCHPC, which depicted 61% higher flexural strength in comparison to NVC. This could be attributed the same reasons as discussed in case of the correlation between the compressive and splitting tensile strengths.

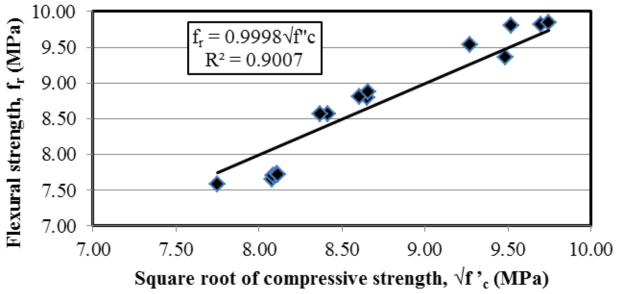

Figure 2. Correlation between compressive strength and flexural strength

C. Correlation between tensile strength and flexural strength

The correlation between the splitting tensile (fsp) and flexural (fr) strengths of the respective SCHPC is presented in figure 3. This figure showed that the compressive and flexural strength of the concrete were strongly correlated with a positive linear relationship. The correlation coefficient was found to be +0.9137, which is an indication of an excellent correlation. The flexural strength was higher than the splitting tensile strength for the respective SCHPC. Nevertheless, they varied similarly with respect to W/B and blended POFA/PBC content and hence, followed a similar trend. Consequently, a strong correlation was observed for the splitting tensile and flexural strengths of the respective SCHPC.

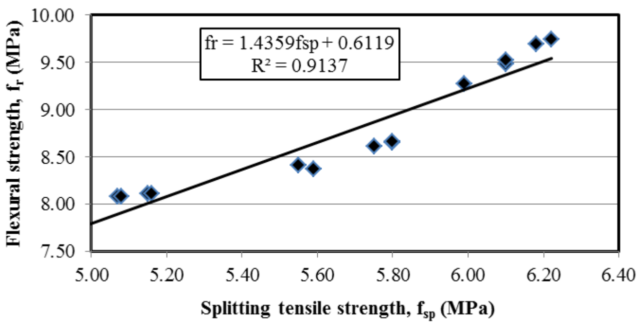

Figure 3. Correlation between tensile strength and flexural strength

D. Correlation between compressive strength and modulus of elasticity

The static modulus of elasticity (Es) of the respective SCHPC was strongly correlated with the square root of the compressive strength (√f'c) with a linearly positive relationship, as shown in figure 4. This relationship was observed for the compressive strength ranging from 53.44 MPa to 94.95 MPa, the static modulus of elasticity ranging from 32.80 GPa to 42.89 GPa. The correlation coefficient was +0.9799 which is an indication of a strong positive relationship. This excellent correlation was observed because both compressive strength and modulus of elasticity varied similarly with the W/B ratio and the blended binder content. According to [21], the relationship between compressive and static- modulus of elasticity is, Es = 4.73√f'c for NVC. In the present study, the relationship obtained for the respective SCHPC was Es = 4.71√f'c, which gives almost the same modulus of elasticity as the NVC. This can be attributed to the same reasons as discussed earlier with respect to the correlation between the compressive and splitting tensile strengths of SCHPC.

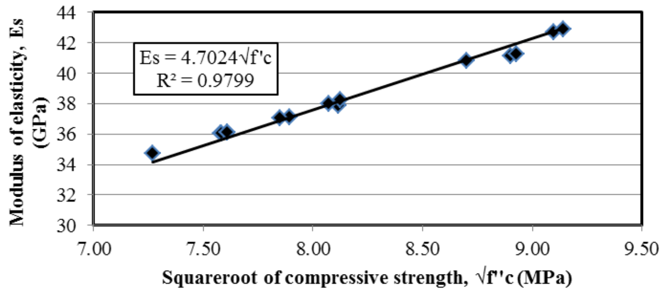

Figure 4. Correlation between compressive strength and modulus of elasticity

E. Correlation between compressive strength and Ultrasonic pulse velocity

The correlation between the compressive strength (f'c) and ultrasonic pulse velocity (UPV) of the respective SCHPC is shown in figure 5. In this study, the ultrasonic pulse velocity varied from 4651 m/s to 5120 m/s whereas the compressive strength ranged from 53.44 MPa to 94.95 MPa. Both properties varied identically with the W/B and blended POFA/PBC content. For these reasons, a strong positive linear relationship with the correlation coefficient of +0.900 was obtained for compressive strength and ultrasonic pulse velocity (figure 5). Similar correlation were also observed by [22] for a semi high-strength concretes incorporating fly ash and blast-furnace slag, and by [23] and [19] for the self-consolidating high-performance concrete incorporating rice husk ash and high-strength self-consolidating concrete containing POFA respectively.

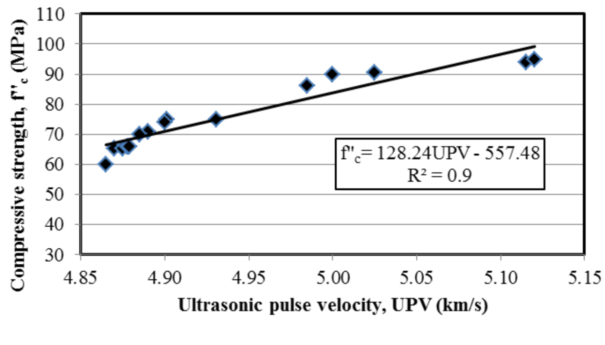

Figure 5. Correlation between compressive strength and Ultrasonic pulse velocity

F. Correlation between compressive strength and porosity

The compressive strength (f'c) and porosity (Pr) of the respective SCHPC were strongly correlated, as highlighted in figure 6. The porosity obtained by cold water method varied from 6.64% to 12.30%. A negative linear relationship –0.8707 was observed between the compressive strength and the total porosity. Such negative linear relationship was observed, due to the fact that the compressive strength and porosity varied inversely with the W/B and the blended POFA/PBC content. Similar relationships were also reported by the other researchers such as [19, 23-25] in the cases of semi high-strength, porous, self-consolidating high-performance concretes and high-strength self-consolidating concrete containing FA, silica fume, RHA and POFA respectively.

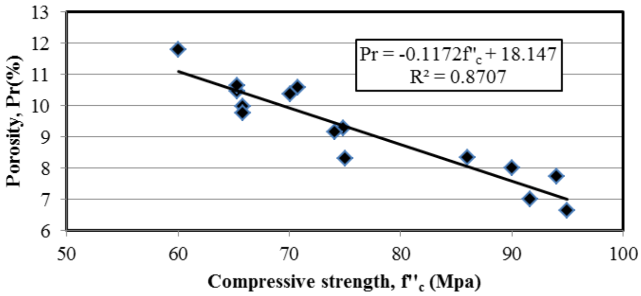

Figure 6. Correlation between compressive strength and porosity

G. Correlation between Ultrasonic pulse velocity and porosity

The correlation between the ultrasonic pulse velocity (UPV) and the total porosity (Pr) of the respective SCHPC is as shown in figure 7. This figure reveals that the ultrasonic pulse velocity and the total porosity have a strong correlation with a negative linear relationship. The correlation coefficient was –0.9245. Such a strong negative correlation was noticed, as the ultrasonic pulse velocity and porosity differed oppositely with the W/B and blended POFA/PBC content. A similar relationship was also observed by [23] in the case of self-consolidating high-performance concrete including rice husk ash and [19] for high-strength self-consolidating concrete containing POFA.

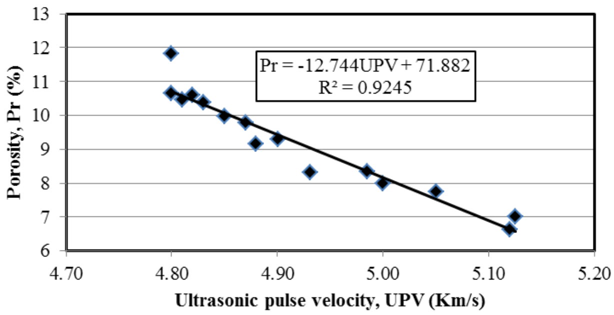

Figure 7. Correlation between Ultrasonic pulse velocity and porosity

H. Correlation between permeability (by water absorption) and porosity

The permeability (Pm, as a function of water absorption) and porosity (Pr) of the respective SCHPC were strongly correlated, as highlighted in figure 8. The porosity obtained by cold water method varied from 6.64% to 12.30%and the permeability obtained by water absorption varied in the range of 3.19 to 6.10%. A positive linear relationship of +0.9666 was observed between the permeability and the total porosity. Such positive linear relationship was observed, due to the fact that permeability and porosity varied similarly with the W/B and the blended POFA/PBC content. Similar relationship was also reported by [23], for SCHPC containing RHA.

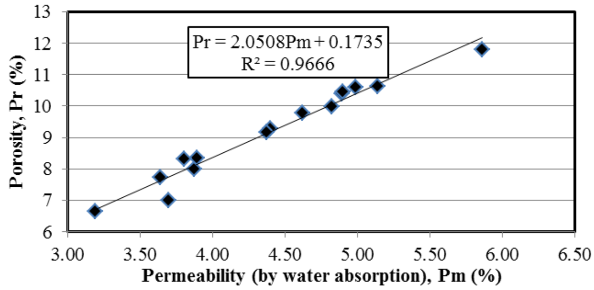

Figure 8. Correlation between porosity and permeability (by water absorption)

I. Correlation between electrical resistivity and rapid chloride ion penetration.

The correlation between the electrical resistivity (ER) and the rapid chloride ion penetration (RCP, measured by the total electrical charge passed) of the respective SCHPC is as shown in figure 9. This figure reveals that the electrical resistivity (ER) and the rapid chloride ion penetration (RCP) have a strong correlation with a negative linear relationship. The correlation coefficient was –0.8762. Such a strong negative correlation was noticed because the higher the ER, better the concrete durability while on the other hand, the lower the RCP, the better the concrete durability. Thus, a negative correlation between the two parameters is a strong indication of excellent durability characteristics. Similar opinion was expressed by [26] with respect to SCC for use in North Dakota transportation projects.

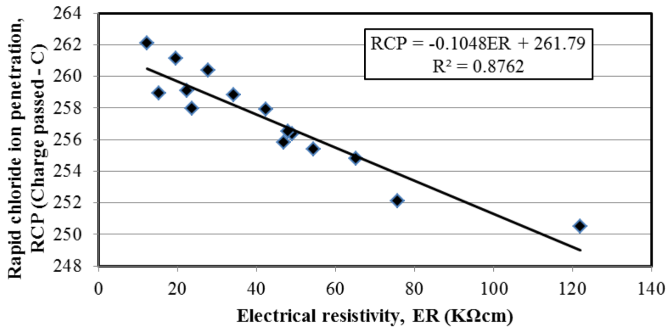

Figure 9. Correlation between electrical resistivity and rapid chloride ion penetration

J. Significance of the Correlations between the hardened properties

The correlations established in the current research are very important tools for predicting the unknown hardened properties of the SCHPC. Thus, the relationships established (equations 1 to 9) provided a platform for determining the unknown hardened properties of concrete without embarking on any experimental investigation process. Consequently, reducing the volume of laboratory work, thereby, reducing time, labor and materials wastage. This on the long run ensures cost reduction.

$$f_{sp} = 0.6901\sqrt{f'c} \quad (1)$$

$$f_r = 0.9998\sqrt{f'c} \quad (2)$$

$$f_r = 1.4359f_{sp} + 0.6119 \quad (3)$$

$$E_s = 4.7024\sqrt{f'c} \quad (4)$$

$$f'c = 128.24\, UPV - 557.48 \quad (5)$$

$$P_r = -0.1172f'c + 18.147 \quad (6)$$

$$P_r = -12.744UPV + 71.882 \quad (7)$$

$$P_r = 2.0508P_m + 0.1735 \quad (8)$$

$$RCP = -0.1048ER + 261.79 \quad (9)$$

IV. CONCLUSIONS

1. A very god correlation was observed between the square root of compressive strength and the splitting tensile strength. The relationship is linear and positive with a correlation coefficient of +0.9135. This is attributed to the similarity in the response to the variation in W/B and the blended POFA and PBC content.

2. The flexural strength and the square root of compressive strength showed an excellent positive linear correlation with a correlation coefficient of +0.9007. This is strongly attributed to the similarity in the effects of both W/B and blended binder on the respective properties.

3. The flexural and splitting tensile strengths have a strong correlation with a positively linear relationship having a correlation coefficient of +0.9137. This is attributed to the same response to the variations in W/B ratio and the blended binder content.

4. The square root of compressive strength was strongly correlated with the modulus of elasticity with a positive linear relationship having a correlation coefficient of +0.9799. Such excellent correlation was observed because both compressive strength and elastic modulus varied similarly with the W/B and blended POFA/PBC content.

5. The compressive strength and ultrasonic pulse velocity were in strong correlation with a positive linear relationship, having a correlation coefficient of 0.9699; such excellent relationship was obtained because both compressive strength and ultrasonic pulse velocity exhibited identical behaviour with respect to W/B and the blended binder content.

6. The compressive strength and porosity were strongly negatively correlated with a correlation coefficient of –0.8707. The negative correlation was observed because compressive strength and porosity varied oppositely with the W/B and blended POFA/PBC content.

7. The ultrasonic pulse velocity and porosity were also strongly negatively correlated with a correlation coefficient of –0.9245. The negative correlation was observed because UPV and porosity varied oppositely with the W/B and blended POFA/PBC content.

8. The Permeability and porosity have a strong correlation with a positively linear relationship having a correlation coefficient of +0.9666. This is also attributed to the same response to the variations in W/B ratio and the blended binder content.

9. The Rapid chloride ion penetration and electrical resistivity were also strongly negatively correlated with a correlation coefficient of –0.8762. The negative correlation was observed because RCP and ER varied oppositely with the W/B and blended POFA/PBC content.

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