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Project: Properties of High-Strength Self-Compacting Concrete (HSSCC) containing waste ceramic powders as supplementary cementitious material

By

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Abstract

High strength self-compacted concrete (HSSCC) is a new type of concrete that combines the advantages of both self-compacted and high strength concretes. HSSCC mixtures required high powder content ranges between 430 and 700 kg/m^3 which is needed to maintain sufficient stability and improving segregation resistance. The use of high cement content to meet the need of high powder is not desirable as it will increase the cost and has other negative effects on concrete properties. The ceramic products have been widely used in several applications in the building construction for a very long time and contribute the highest percentage of wastes within the Construction and Demolition (C&D). Ceramic wastes are disposal to landfills and can leads to great environmental problems. Ceramic waste powder (CWP) has previously been used as a partial cement replacement in concrete. However, limited research has been undertaken to utilize CWP in self-compacting concrete (SCC). This research presents a study on using two type of ceramic wastes as partial replacement of cement in HSSCC mix base on the source of raw materials: red ceramic waste powder (RCWP) from wall tiles ceramic of red clay and white ceramic waste powder (WCWP) from sanitary ware ceramic of white clay. For this research, a total of eight mixes were made of OPC as a control mix (HS-C), OPC replaced with 10% silica fume (HS-10SF), OPC replaced with 10%, 15% and 20 % of RCWP (HS-10RC, HS-15RC and HS-20RC respectively) and OPC replaced with 10%, 15% and 20 % of WCWP (HS-10WC, HS-15WC and HS-20WC respectively). Tests have been conducted on the fresh properties, such as filling ability, passing ability and segregation resistance, as well as compressive strength, flexural strength to check the effect of inclusion CWP on HSSCC. The results showed that the inclusion of RCWP and WCWP improve the fresh properties of the HSSCC mix. On the other hand, the compressive strength and flexural strength of HSSCC couniting RCWP and WCWP registrar higher result than control mix with only OPC on all ages. In addition, HS-10SF showed better fresh properties and higher strength than HSSCC-CWP and HS-C. Conclusively, CWP can be used as a cement replacement to produce HSSCC with an improvement in its properties.

1. Introduction

Producing High strength concrete is always one of the major goals of concrete technology. For more than 30 years high strength concretes with compressive strength ranging from 40 MPa up to 140 MPa have been used worldwide in large buildings, towers and long span bridges buildings. Commonly high strength concrete has low (W/C) ratio which means low workability and inability to fill the forms corners without external actions.

On the other hand, Self-compacting concrete, a recent innovation in concrete technology is being regarded as one of the most promising developments in the construction industry due to numerous advantages of it over conventional concrete. Self-consolidating concrete, as the name indicates, is a type of concrete that does not require external or internal compaction, but it becomes levelled and compacted into every corner of a form work, purely by means of its self-weight thus eliminating the need of vibration or other types of compacting effort [1]

High strength self-compacted concrete (HSSCC) is a new type of concrete that combines the advantages of both self-compacted and high strength concretes. HSSCC has been developed to show good fresh properties and exhibit high strength and excellent durability characteristics [2–4]. HSSCC has been used to different types of structural applications for which densely congested reinforcement concrete elements and the pumping to high levels is needed. It can be used in many applications, such as high-rise buildings, tunnel lining repairs, and congested foundations [5,6]. HSSCC need high amounts of cement and the requirement for high powder content in HSSCC is usually met by using mineral admixtures such as slag, fly ash and/or less reactive filler materials such as limestone powder and granite powder.

Clay minerals become highly reactive when they are incinerated at temperatures between 600 and 900 ^{o}C and then ground to cement fineness [7]. They are mainly formed by siliceous and aluminous compounds. The loss of water due to thermal treatments causes destruction of their crystalline structure, and they are converted into unstable amorphous state [8]. If they are then mixed with calcium hydroxide and water they undergo pozzolanic reaction and form compounds with enhanced strength and durability.

A huge amount of ceramic wastes arose from both manufacturing and application and also maintenance stages. Although there are no realistic solutions of the management of these wastes, some of the researchers have been used ceramic waste as aggregate or filler in traditional concrete mixes [9–13]. Waste ceramic materials may become a cheaper and often produces calcined clays that result from burning illite-group clays which are commonly used in the production of red-clay ceramic products. The residues of ceramic bricks and floor and roof tiles ground to a suitable fineness can though become active pozzolans [14-16]. So, they have a potential to be used in mortar and concrete. Torkittikul, and Chaipanich (2010) investigated the feasibility of using ceramic waste and fly ash to produce mortar and concrete, and they indicated that the compressive strength of ceramic waste concrete was found to increase with ceramic waste content and was optimum at 50% for the control concrete [17]. Medina Martinez et al. (2009) reported that, ceramics industry wastes (recycled ceramic aggregates) are suitable for the manufacture of concrete [18]. Alves et. al. (2014) pointed out that, regarding the mechanical performance, in terms of compressive and tensile strength, the use of ceramic recycled aggregates for concrete is suitable [19,20]. In this study, fine grounded ceramic were used to product High strength self-compacted concrete with the idea of having a high potential of filler effect.

2. Problem statement

HSSCC mixtures include high powder content ranges between 430 and 700 kg/m^3 [21,22], which is needed to maintain sufficient stability/cohesion of the mixture and hence improving segregation resistance. The use of high cement content to meet the need of high powder is not desirable as it will increase the cost, high hydration heat, risk of quick setting and has other negative effects on concrete properties. In addition to that, one of the big problems of cement production is high carbon emission during raw material procurement and production of cement [23,24]. Recently, various studies have been performed in different laboratories in an attempt to find alternative raw materials can be used as partial replacement of cement.

Ceramic materials contribute the highest percentage of wastes within the Construction and Demolition (C&D) wastes (54%) [25]. Ceramic wastes are dumped in landfills and can cause soil, air and groundwater pollution making a serious environmental problem. Fine grounded ceramic waste powder (CWP) is characterized by chemical composition which is mainly SiO2 and Al2O3 (i.e. more than 60%). This makes CWP a very good candidate to be used as filler in HSSCC. Therefore, the utilization of CWP would achieve sustainable HSSCC with strong environmental incentive.

3. Research objectives

The main objective of this research is to investigate the effectiveness of varied proportion (0, 10, 15 and 20 wt.% of cement) of red and white ceramic waste powder on the properties of high strength self-compacted concrete (HSSCC). Furthermore, this research is also aimed at reducing the construction costs and decreasing the solid wastes negative impacts on the environment.

4. Experimental work

4.1 Materials

4.1.1 Cement

There are many kinds of cement with different compositions and produced for different function. The cement used in this experiment is ordinary Portland cement (Tasluja). Table 1 shows the chemical properties of Tasluja cement.

Table 1: Mineral composition of Tasluja cement

Compositions	OPC (%)	Compositions	OPC (%)
SiO_2	20.59	Loss of Ignition	0.8
Al_2O_3	5.92	Insoluble Residue	1.75
Fe_2O_3	3.29	C_3S	64.68
CaO	64.16	C_2S	23.2
MgO	2.20	C_3A	5.15
SO_3	2.21	C_3AF%	9.97
Free Lime	0.76		

4.1.2 Silica Fume

In this experiment, a grey densified silica fume type (MegaAdd MS) with specific gravity of 2.40 and bulk density of 600kg/m^3 has been used as shown in Figure 1. Over size particles retained on 45micron sieve. The effect of silica fume can be explained by its pozzolanic reaction with calcium hydroxide released from cement hydration and filling effect in the voids among cement or other powder material particles [26].

Figure 1: Grey densified silica fume

4.1.3 Ceramic Waste Powder (CWP)

Ceramic wastes can be divided into two groups, depending on the source of raw materials. The first group includes products of burned red clay (bricks, structural wall and floor tiles, roof tiles). Products made of white clay: technical ceramics (ceramic electrical insulators), ceramic sanitary ware (washbowls, lavatory pans, bidets, bathtubs), medical and laboratory vessels, belong to second group. Second group producers use red and white clay, nevertheless, the usage of white clay is more frequent and much higher in volume.

In this research two types of ceramic wastes were used: red ceramic waste powder (RCWP) from wall tiles ceramic of red clay and white ceramic waste powder (WCWP) from sanitary ware ceramic of white clay as shown in Figure 2. Ceramic wastes were firstly grounded in Los Angeles abrasion machine and then sieved in 300-micron sieve.

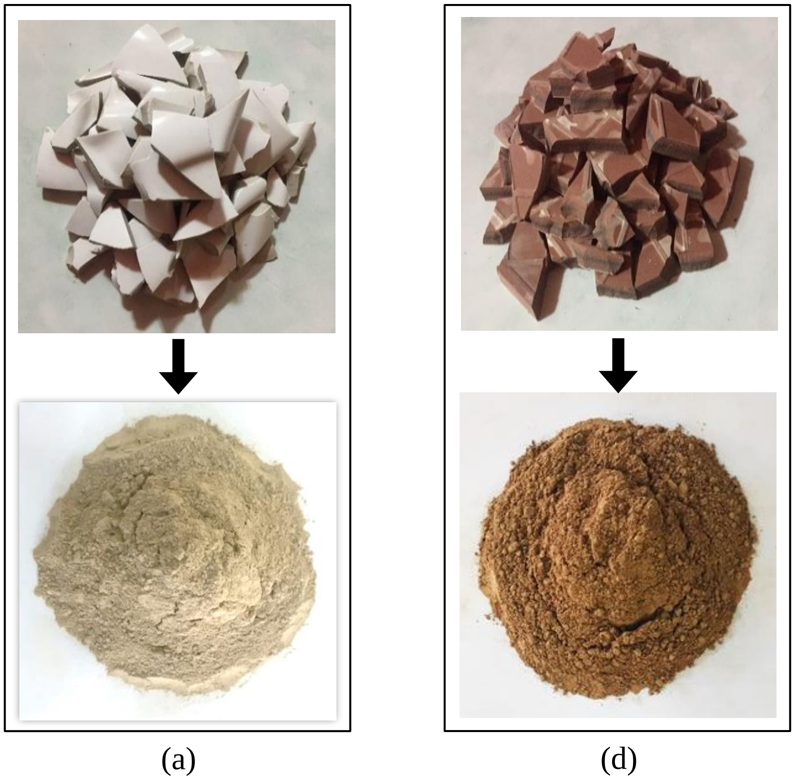
(a) (d)

Figure 2: Waste ceramic preparation process: (a) White ceramic waste powder-WCWP (b) Red ceramic waste powder-RCWP

4.1.4 Aggregate

In this experiment, the local available aggregate of Basrah quarries was used. Zubair sand with a maximum size of 0.6 mm as fine aggregate and Jabal Sanam gravel with a maximum size of 12 mm as a coarse aggregate were used in the HSSCC mixtures. Table 2 shows the properties of fine and coarse aggregate.

Table 2: Properties of fine and coarse aggregate

Materials	Specific gravity(g/cm^3)	Absorption
Zubair sand	2.62	1.5 %
Jabal Sanam gravel	2.58	1.0%

4.1.5 Water

R.O water was used for mixing and curing of concrete throughout the experiment.

4.1.6 Superplasticizer

The superplasticizer used in this study is Sika ViscoCrete Hi-Tech 1316 as shown in Figure 3. In order to produce HSSC. Sika ViscoCrete is a modified polycarboxylates based polymer with specific gravity 1.123 at 25°C. The use of superplasticizer is to improve the workability of the mixtures.

Figure 3: Sika ViscoCrete Hi-Tech 1316 (superplasticizer)

4.2 Mix proportions of HSSCC

Self-compacted concretes typically have a higher content of fine particles and improved flow properties compared to the normal concrete. It has three essential properties when the concrete is fresh: filling ability; resistance to segregation; and, passing ability. SCC consists of cement, fine and coarse aggregates, mineral and chemical admixtures, and water. In order to produce HSSCC with compressive strength between 40-100 MPa, the range of powder content in the production of HSSCC varies between 430 and 700 kg/m^3 [21,22]. The coarse to fine aggregate ratio in the mix is reduced in order to reduces aggregate interlock and bridging when the concrete passes through narrow openings between reinforcement and increases the passing ability of the SCC. Mix design method proposed by Su et al. [27] and guidelines provided by EFNARC [28,29] adopted in this study in order to reach an initial mix proportioning for HSSCC. The properties of different combinations of the basic constituents were compared in trial batches. The most promising combination of basic components has been chosen.

In this study, HSSCC with cement contains 650 kg/m3, water/binder ratio of 0.30 and superplasticiser dosage of 2.5% by mass of binder prepared as control mix (HS-C). In addition, HSSCC with 10% silica fume as partial replacement of cement (HS-10SF) also prepared to increase cohesion and segregation resistance of the mixture. On the other hand, two type of waste ceramic were used in the production of HSSCC, first type is red ceramic waste powder as partial replacement of cement at level 10%, 15% and 20% (HS-10RC, HS-15RC, and HS-20RC, respectively) and second type is white ceramic waste powder as partial replacement of cement at level 10%, 15% and 20% (HS-10WC, HS-15WC, and HS-20WC, respectively) as shown in Table 3.

Table 3: Mix proportions of HSC & NSC used in the present study

Materials (kg/m^3)	HS-C	HS-10SF	HS-10RC	HS-15RC	HS-20RC	HS-10WC	HS-15WC	HS-20WC
Cement	650	585	585	552.5	520	585	552.5	520
Silica fume	--	65	--	--	--	--	--	--
RCWP	--	--	65	97.5	130	--	--	--
WCWP	--	--	--	--	--	65	97.5	130
Gravel	772	772	772	772	772	772	772	772
Sand	772	772	772	772	772	772	772	772
Water	185.25	185.25	185.25	185.25	185.25	185.25	185.25	185.25
Superplasticizer	16.25	16.25	16.25	16.25	16.25	16.25	16.25	16.25

4.3 Samples preparation

Mixing of HSSCC was done using a drum type mixture. For each mixture, 9 cubes (150×150×150) mm and 6 beams (100×100×500) were prepared. After casting the specimens were cured in water at room temperature 27 ± 2 °C until they are required for testing.

4.5 Test procedures

4.5.1 Evaluation of self-compatability of fresh concrete

A number of test methods such as slump-flow, V-flow time, L-box, and J-ring tests are in use for the evaluation of self-compacted properties of the concrete. These test methods have two main purposes. One is to judge whether the concrete is self-compactable or not, and the other is to evaluate the deformability or viscosity for estimating proper mixture proportioning if the concrete does not have sufficient self compactability [30]. The following tests were conducted in this investigation:

4.5.1.1 Slump-flow test

Slump-flow testing is the simplest and most commonly adopted test method for evaluating the flowability quality of self-consolidating concrete according to ASTM C 1611 [35] as shown in Figure 4. The acceptance value of slump test for SSC is ranging between 600 to 800 mm [28]. Flowing time from the initial diameter of 200 mm (at the base of the slump cone) to 500 mm, designated as T500 test, is used for a secondary indication of flow.

Figure 4: Slump flow test

4.5.1.2 J-ring test

The J-ring test is another type of method for the study of the blocking behavior/passing ability of self-compacting concrete as shown in Figure 5. The acceptance value of J-ring flow diameter ranging between 580-780 and J-Ring height H_{in}-H_{out} ranging between 0-15mm [28].

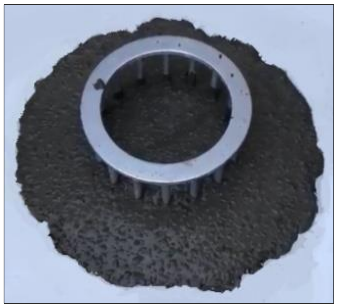

Figure 5: J-ring test

4.5.1.3 V-funnel test

The V-funnel test was conducted to measure the filling ability of the mixes as shown in Figure 7. The acceptance value of V- Funnel ranging between 6 to 12 second [28].

4.5.1.4 L-box test

This test gives an indication of the filling, passing, and segregation-resisting ability of the concrete as shown in Figure 8. The heights of concrete at both ends of the apparatus (H1 and H2) are measured to determine L-box results. The accepted ratio of L-Box ranging between 0.75 to 1[28].

Figure 6: V-Funnel test

Figure 8: L-Box test

4.5.2 Compressive strength

In this investigation, about 63 samples of 150 mm concrete cubes were tested using 2000kN concrete compression machine according to BS EN 12390-3 [32] as shown in Figure 9. Compressive strength test for each mixture was performed at the ages of 3, 7 and 28 days. The samples are loaded to failure in a compression testing machine according to BS EN 12390-4 [33].

Figure 9: Compressive strength machine

4.5.3 Flexural strength test

This test method covers the determination of the flexural strength of concrete by the use of a simple beam with third-point loading in according to ASTM C78 [34]. Results are calculated as the modulus of rupture using the following relation.

$$f_r = \frac{Pl}{bd^2},$$

where f_r is the modulus of rupture, P is the maximum load value, L is the length of beam, b is the average width of specimen and d is the average depth of the specimen.

5. Results and Discussion

5.1 Fresh properties

The fresh concrete was evaluated by conducting the filling ability, passing ability, and segregation resistance tests. Table 4 shows the fresh properties of HSSCC mixes and Table 5 shows the HSSCC fresh properties acceptance values.

5.1.1 Filling ability

Filling ability refers to the ability of concrete to flow horizontally and reach all the corners of a formwork under its self-weight of concrete without vibration [28]. The filling ability of the different mixes of HSSCC was examined with respect to the slump flow, *T*500 spread time, and V-funnel flow time.

For all the mixes, the slump flow was in the range of 690–760 mm, which is in agreement with the EFNARC standard [28]. As shown in Table 4, it can be seen that the mixes incorporating red and white ceramic waste powder could enhance the slump flow as compare with the control mix without ceramic and the slump increase as the ceramic contain increase. This may because the fine particles of the ceramic waste powder are adsorbed on the oppositely charged surfaces of cement particles and prevent them from flocculation. Thus, the cement particles are dispersed effectively and will not trap large amounts of water. On the other hand, RCWP record an increase in the workability than WCWP as shown in Figure 10. In addition, the inclusion of silica fume with 10% record the highest slump diameter of 760mm as compare with all other mixes. Similar findings on high-performance concrete containing high-volume fly ash were reported by Malhotra et al. [36].

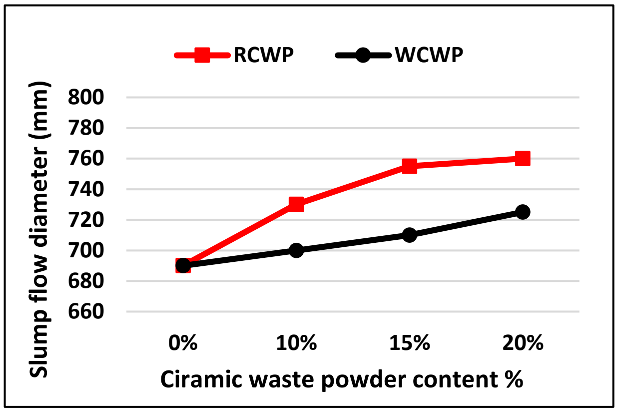

Figure 10: Slump flow for HSSCC with RCWP and WCWP

In addition, the time taken for concrete to reach 500mm after lifting the slump cone (*T*500mm) was measured at the mean time of conducting the slump flow as shown in Table 4. HSSCC with 10% silica fume have the lowest T500 time of 6 second. In addition, Figure 11 show that as the ceramic waste powder content increased, the *T*500 time decreased. The lower *T*500 indicates good filling ability. From these tests, it can be concluded that the white and red ceramic waste powder significantly improved the workability in terms of slump flow and *T*500 compared to control mix.

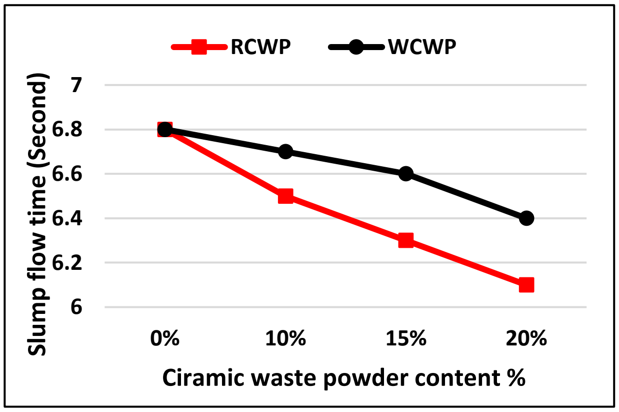

Figure 11: T500 for HSSCC with RCWP and WCWP

The V-funnel test was conducted to measure the filling ability of the mixes. The values of V-funnel vary in the range of 11–8.8 second as shown in Table 4. These values are considered to be appropriate and fulfill the requirement of

EFNARC [28]. It can be seen from the result in Figure 12 that as the content of the WCWP and RCWP increased, the V-funnel time decreased linearly and HS-RC register lower V-funnel time than HS-WC and higher than HS-10SF. In addition, the shorter flow times indicate greater flowability. This improvement can be attributed to the low plastic viscosity of the mixes containing ceramic powder. The results obtained from this study were in agreement with previous studies on self-compacting concrete containing fly ash up to 50% replacement [37].

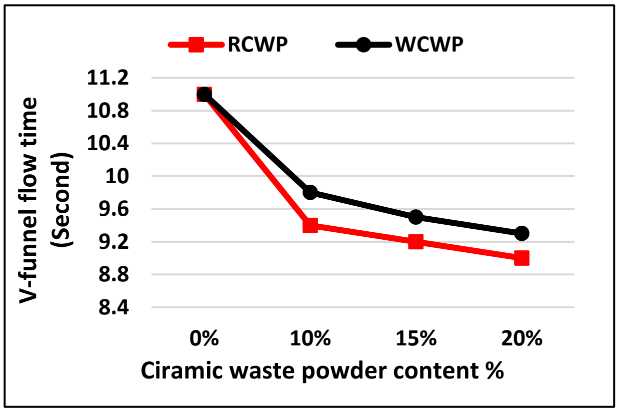

Figure 12: V-funnel flow time for HSSCC with RCWP and WCWP

Table 4: Fresh properties of HSSCC mixes

Test type	HS-C	HS-10SF	HS-10RC	HS-15RC	HS-20RC	HS-10WC	HS-15WC	HS-20WC
Slump flow diameter (mm)	690	760	730	755	760	700	710	725
Slump flow T_{500} (second)	6.8	6	6.5	6.3	6.1	6.7	6.6	6.4
J-Ring flow diameter (mm)	675	740	715	735	745	680	700	710
J-Ring height H_{in}-H_{out} (mm)	9	5	7	6	6	8	7	7
L-Box ratio	0.76	0.88	0.86	0.86	0.87	0.83	0.85	0.86
V-Funnel (second)	11	8.8	9.4	9.2	9	9.8	9.5	9.3

Table 5: Fresh properties acceptance values [28]

Test type	Acceptance range
Slump flow diameter (mm)	600-800
Slump flow T_{500} (second)	2-7
J-Ring flow diameter (mm)	580-780
J-Ring height H_{in}-H_{out} (mm)	0-15
L-Box ratio	0.75-1.0
V-Funnel (second)	6-12

5.1.2 Passing ability

Passing ability can be defined as the ability of SCC to pass congested reinforcement and small openings under its self-weight without vibration. This was evaluated by conducting J-ring and L-box tests.

The J-ring test was measured with respect to the difference between the height of the concrete inside and outside of J-ring bars; the diameter of the concrete was also measured. The differences in height of the different mixes varied in the range of 5–9 mm, as shown in Table 4. HS-10SF and HS-20RC showed the lowest value (5 mm and 6mm, respectively) due to the lower viscosity and shear stress, which allowed the concrete to flow more freely. Besides that, all mixes contain RCWP showed lowed value than WCWP as shown in Fig. 13 and all mixes contain CWP showed lower value than the control mix with only cement. In addition, the diameter of the concrete was measured, and the results showed that the HS-20RC exhibited the higher diameter of concrete containing red ceramic as shown in Fig. 14 and all mixes contain CWP showed high diameter than control mix with only cement. This may due to the lower specific gravity of ceramic compared to concrete made with only cement.

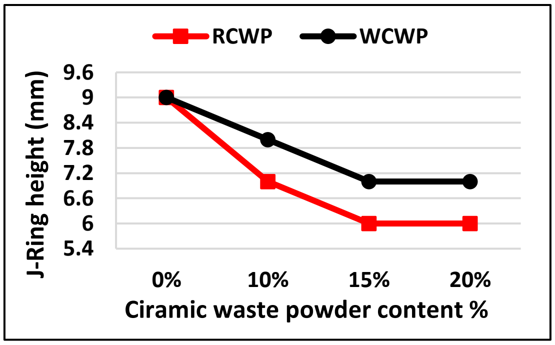

Figure 13: J-Ring height for HSSCC with RCWP and WCWP

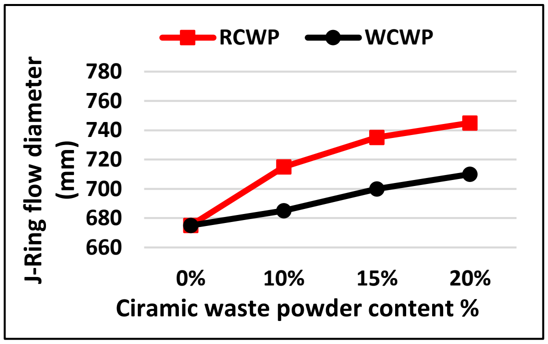

Figure 14: J-Ring flow dia. for HSSCC with RCWP and WCWP

The L-box test is normally used to assess the passing ability of SCC when it is subjected to reinforcement blocks [28]. The test results showed that as the red and white waste ceramic powder content increased, the value of the L-box also increased and mixes contain RCWP record higher L-box ratio than mixes contain WCWP, as shown in Figure 15. This can be attributed to the lower viscosity and yield value of concrete containing the ceramic wastes. On the other hand, all mix contain CWP showed high diameter than HS-C and lower diameter than HS-10SF.

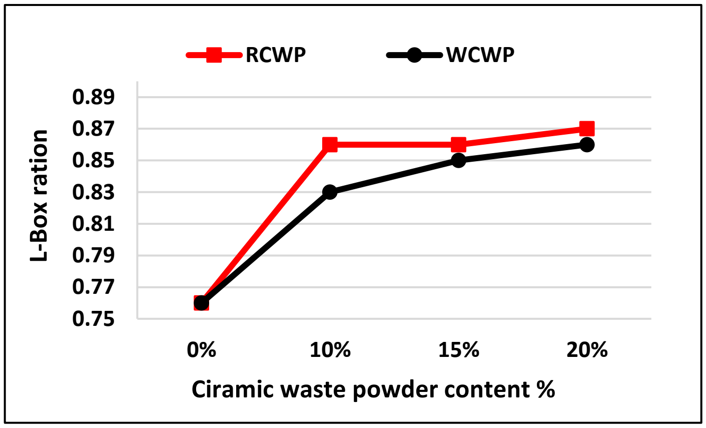

Figure 15: L-Box ratio for HSSCC with RCWP and WCWP

5.1.3 Segregation resistance

All HSSCC mixes were visually inspected during the slump flow, J-ring, and L-box tests. It was observed that there was no segregation or bleeding in any of the mixes. Segregation resistance is a very important factor in HSSCC. The mix compositions must remain homogeneous and uniform during and after the process of transport and placing [28,38]. Furthermore, it should be ensured that all the aggregate is relatively equivalent at all locations and at all levels to avoid any deformability and blocking [39].

5.2 Compressive strength

The specimens were tested at 3, 7, and 28 days after curing in water. Figure 16 and Table 6 present the compressive strength results of HSSCC mixes. The lowest compressive strength of 45.9 MPa was recorded by control mix with only cement (HS-C) at 3 days, while the highest compressive strength of 85 MPa was achieved by HSSCC mix with 10% silca fume (HS-10SF) at 28 days. It is clear from the overall results that the inclusion of Ceramic waste powder (CWP) and silica fume has significant influence on strength and strength development characteristics of the HSSCC mixes when compared with the control mix with only cement.

HSSCC mixes with white ceramic waste powder (WCWP) showed higher compressive strength than red ceramic waste powder (RCWP) with 28 days strength value 45.9, 53, 51.8, 49, 51,60.2 and 55.4 MPa for HS-C, HS-10RC, HS-15RC, HS-20RC, HS-10WC, HS-15WC and HS-20WC, respectively. In addition, the results show that the compressive strength of HSSCC with RCWP decreases as the percentage of RCWP replacement increases. Besides that, the result of HSSCC mixes with WCWP showed an increase in compressive strength at 15% WCWP and reduction in strength at 20% WCWP as shown in Figure 16. Moreover, All HSSCC mixes with CWP recorded higher compressive strength than HS-C at 3,7 and 28 days. The increase in the compressive strength of CWP-HSSCC could be attributed to the fineness of CWP particles, which filled the voids between the cement and the fine aggregates. Besides that, the SiO2 contained in POFA reacts with the Ca(OH)2 generated by the hydration process of cement to form secondary calcium–silicate–hydrate (C—S—H) and improves bonding between the fine aggregates and pastes, which lead to improve the compressive strength. Similar results for the self-compacting concrete and normally vibrated concrete containing rice husk ash (RHA) showed that the early age compressive strength for 10% and 20% cement replacement was higher than the control concrete due to the higher fineness of RHA [37,40].

Table 6: Compressive strength values HSSCC mixtures

	Compressive strength (MPa)							
Age (days)	**HS-C**	**HS-10SF**	**HS-10RC**	**HS-15RC**	**HS-20RC**	**HS-10WC**	**HS-15WC**	**HS-20WC**
3	45.9	59	53	51.8	49	51	60.2	55.4
7	53	68	62.3	60	56.67	59.3	69.8	59.3
28	64	85	73.65	72	67.98	69	84	72.5

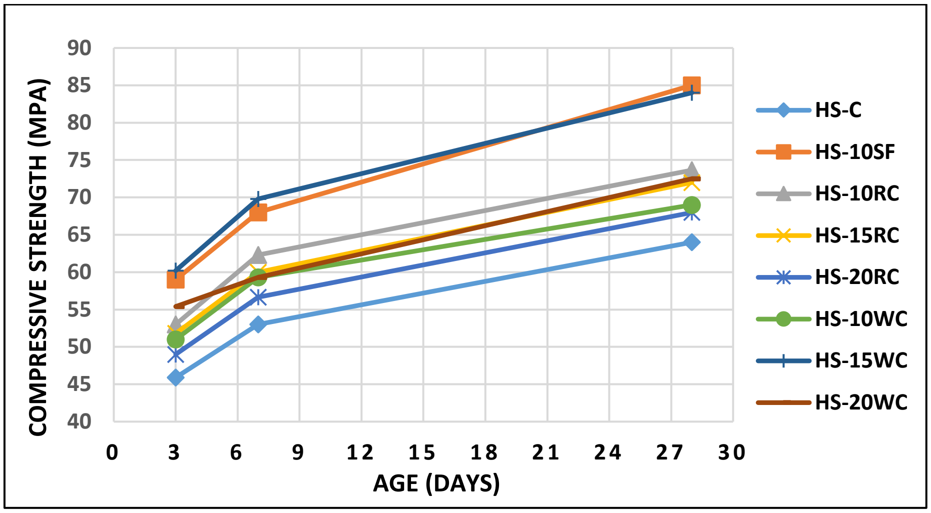

Figure 16: Compressive strength development of HSSCC mixtures

5.3 Flexural strength

Figure 17 shows the flexural strength test results for HSSCC samples at test ages of 28 days. The result showed that all HSSCC mixes register high flexural strength than control mix (HS-C) with value 6.24, 6.7, 6.55, 6.36, 6.3, 6.42, 6.6 and 6.49MPa for HS-C, HS-10SF, HS-10RC, HS-15RC, HS-20RC, HS-10WC, HS-15WC and HS-20WC, respectively. Furthermore, as the inclusion of RCWP increase the flexural strength decrease. HSSCC with 10% silica fume register the highest flexural strength of 6.7 MPa. In addition, HSSCC-WCWP mixes showed higher flexural strength than HSSCC-RCWP mixes and HS-15WC showed the highest flexural strength as compared with HSSCC-CWP mixes.

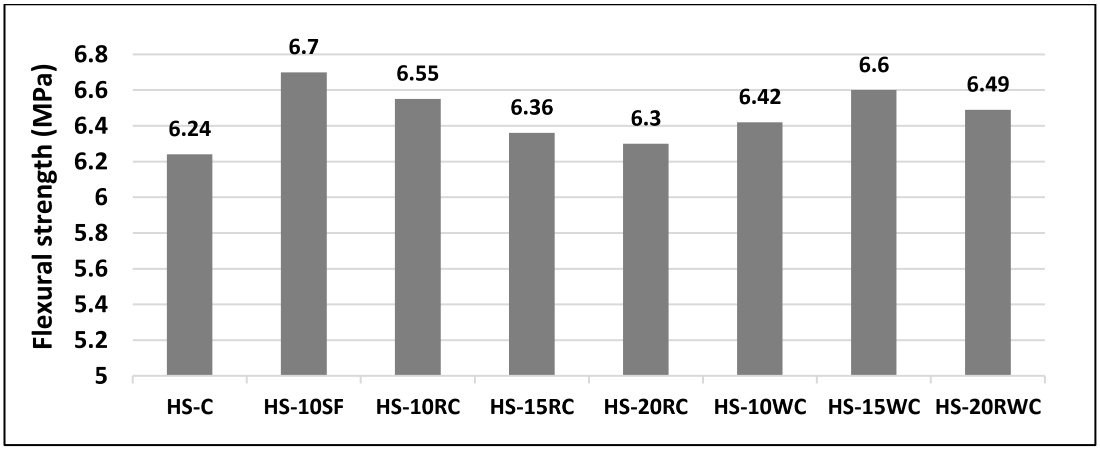

Figure 17: Flexural strength of HSSCC mixtures at 28 days

6. Conclusion

1- It is possible to produce HSSCC using materials which are available at the local markets.
2- Ceramic being a waste material, can be good pozzolanic material on account of its higher silica content.
3- The inclusion of ceramic waste powder (CWP) tend to increase the workability of high strength self-compacted concrete (HSSCC) at constant water/bender ratio with increase in workability as the inclusion of CWP increase.
4- HSSCC_S containing RCWP report better fresh properties than HSSCC containing WCWP and all HSSCC containing CWP exhibited better fresh properties than the control mix with only cement (HS-C).
5- The inclusion of the silica fume as replacement of cement record better fresh properties as compare with control mix (HS-C) and HSSCC mixes containing CWP.
6- HSSCC mixes containing RCWP registered higher compressive strength than control mix with only cement while the compressive strength decreases with the increase RCWP replacement level such that 10% RCWP (HS-10RC) exhibited highest compressive strength of 73.65 MPa at 28 days compared to HS-15RC and HS-20RC.
7- HSSCC mixes containing WCWP exhibited higher compressive strength than HSSCC mixes with RCWP and control mix (HS-C). HSSCC with 15%WCWP register the highest compressive strength of 84MPa at 28 days compared with HSSCC mixes containing RCWP and WCWP.
8- Flexural strength of HSSCC containing CWP register higher flexural strength than control mix (HS-C) and 15% WCWP replacement register the highest flexural strength of 6.6 MPa.
9- Flexural strength of HSSCC with 10% silica fume (HS-10SF) exhibited the highest flexural strength compared with all other mixes of HSSCC.

7. References

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