Rheological and Mechanical Characteristics of Self-Compacting Concrete Containing Corncob Ash

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Abstract
This paper examines the effects of replacing ordinary Portland cement (OPC) with corncob ash (CCA) on the rheology and strength properties of self-compacting concrete (SCC). The rheology and compressive strength properties of different mixes of CCA-blended self-compacting concrete (CCA-SCC) were compared with the conventional SCC with and without superplasticizer at varying water-binder ratios. These properties were determined on fresh and hardened concretes respectively. The CCA-SCC mixes with superplasticizer fulfilled European Federation of National Associations Representing for Concrete (EFNARC) requirements for SCC flow properties except those in excess of 15 % CCA and those with neither CCA-blended cement nor admixture. A higher dosage of superplasticizer or water-binder ratio was required to meet the standard flow requirements. The CCA-SCC mixes exhibited the tendency for more strength beyond 90-days due to pozzolanic reactions. The paper revealed that CCA enhanced the rheological properties of SCC, while the rate of strength development was enhanced after 28-days curing due to pozzolanic activities.

Keywords: density, pozzolanic, strength, superplasticizer, water-binder.

1.0 INTRODUCTION

Concrete is the most versatile heterogeneous construction material and the impetus of infrastructural development of any nation. Civil engineering practice and construction works around the world depend to a very large extent on concrete. Olafusi and Olutoge (2012), found that the reuse or recycling of locally available supplementary cementitious materials (SCM) and agro-allied wastes in concrete production tremendously enhance the economic power of rural dwellers and also mitigate the challenges of solid waste management. The pioneering reports (ACI, 2005; Bartos, 1993; Okamura and Ouchi, 2003) extensively described self-compacting concrete or self-consolidating concrete (SCC) as a highly flow-able, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation. When large quantity of heavy reinforcement is required in a reinforced concrete member, it is relatively difficult to ensure that concrete entirely fills the formwork without any honeycomb. Thus, full consolidation without voids or honeycombs through compaction by manual or mechanical vibrators is very impractical in this situation, as it generates delays and additional cost in the projects and hence, the development of SCC (Olafusi *et al.*, 2015).

The biggest differences between SCC and the conventional concrete is its limitation to coarse aggregate size, the incorporation of admixtures and sometimes inert materials. The use of mineral admixtures in the production of SCC has been widely reported by concrete technology research scholars, to significantly enhance the rheology and strength properties of SCC. Salami *et al.* (2014) investigated the flow criteria, compressive strength and durability (chloride permeability, corrosion and sulfate resistance) characteristics of SCC prepared to utilize crushed limestone powder (CLSP) as partial replacements for cement and aggregates. Their findings revealed that CLSP-aggregate replacement was more superior to CLSP-cement substitution in terms of compressive strength and significant cost savings especially, with a high amount of substitution in regions where materials like fly ash and silica fume have to be imported from other countries. Yahia *et al.* (1999) investigated the effect of rheological parameters on self-compatibility of concrete containing various mineral admixtures and observed that the use of mineral admixtures such as fly ash and blast furnace slag could increase the slump of the concrete mix without increasing its cost, while reducing the dosage of superplasticizer needed to obtain similar slump flow compared to concrete made with Portland cement only. Ede and Adegbite (2014) in their study on the rheological properties of developed SCC using various dosages of limestone powder and super-plasticizer confirmed that limestone powder can be used to enhance the rheological properties of SCC. Siad *et al.* (2015) studied the effects of mineral admixture type on the behavior of SCC in magnesium sulphate environments over the course of 4 years exposure. Their results indicated that among the mineral admixtures tested, natural pozzolans exhibited superior long-term durability performance in the magnesium sulphate environment. Siddique (2011) reported in his investigation on the properties of SCC made with class-F fly ash that the 28-day compressive strength of the mixes reduced with increased fly ash replacement. Chopra *et al.* (2015) investigated the effect of replacing cement content with rice husk ash (RHA) as supplementary cementitious materials in SCC. Their findings indicated that the inclusion of RHA as a partial replacement for cement improved the strength and durability properties for replacements not exceeding 20% replacement with reduced porosity compared to mixes without the supplementary cementitious material. Pai (2014) found SCC to effectively reduce thermally-induced cracking of concrete due to the heat of hydration, increase workability and long-term properties of concrete, which significantly reduce the cost of concrete production. This has greatly influenced its use in developing nations. SCC has been reported to show significant enhancement of strength and stiffness compared to the conventional concrete. The incorporation of a high volume of pozzolanic materials in SCC mixes have also been successfully developed (Ofuyatan, 2014). This study was prompted by the fact that most physical and durability properties of concrete are primarily dependent on its rheology and strength characteristics. Although in practice, most concrete is subjected simultaneously to a combination of compressive, shearing, and tensile stresses in two or more directions; the uniaxial compression tests are relatively easy to perform in the laboratory and widely regarded as a reliable index of the integrity of concrete structures (Barr *et al.*, 2009). The compressive strength of concretes is several times greater than other strength types. Therefore, majority of concrete structural elements are designed to take advantage of a higher compressive strength concrete (IDE, 2015).

2.0 MATERIALS AND METHOD

2.1 Materials

Corncobs were sourced from rural Maize farmers in Sagamu, Ogun State, Nigeria. The samples were sun-dried in open air to reduce moisture (**Figure 1a**), milled to shreds (**Figure 1b**) and placed in a porcelain crucible inside the muffle carbonite furnace (**Figure 1c**) at a temperature of 650 ^{o}C for 5 hours to completely remove the carbonaceous material until a white substance was formed from the original corncob sample as shown in Figure 1d. Ordinary Portland cement (32.5 grade), sharp river sand were used as fine aggregate (FA) and crushed granite stones were used as coarse aggregate (CA). These materials were sourced from local suppliers in Lagos State, Nigeria and subjected to particle-size analysis to determine their grain sizes. Conplast SP430 Superplasticizers (a chloride free, super plasticising admixture based on selected sulphonated naphthalene polymers) was used in the study.

(a) (b) (c) (d)

Figure 1: Incineration of milled corncobs (a) Corncobs (b) milled Corncobs (c) muffle carbonite furnace (d) carbonized Corncobs powder

2.2 Mix Proportions

A total of 180 concrete samples were produced from twelve different mixes of fifteen samples of 0.38 and 0.40 water-binder ratios (w/b) as presented in **Table 1**. The CCA was blended with cement in 0, 5, 10, 15 and 20 %. Samples 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 had 2 liters per 100 kg of cement dosage of water-reducing superplasticizer admixture, while no admixture was added to samples 11 and 12. Samples 1 and 2 of 0.38 and 0.40 w/b respectively served as SCC control sample with 0 % CCA replacement for cement. Samples 3 and 4 of 0.38 and 0.40 w/b respectively had 5 % CCA-SCC; samples 5 and 6 of 0.38 and 0.40 w/b respectively had 10 % CCA-SCC; samples 7 and 8 of 0.38 and 0.40 w/b respectively had 15 % CCA-SCC and samples 9 and 10 had 20 % CCA-SCC. Samples 11 and 12 were similar to samples 1 and 2 respectively except that they did not contain any admixture. Batching by weight approach (using a dial spring weighing scale) was adopted in the study.

2.3 Rheological Properties

The rheological properties (fresh concrete properties) include the passing ability, flowability and segregation resistance of the concrete mixes while in their fresh or plastic state. Passing ability of the mixes was examined by the L-box apparatus; slump flow examined using an Abrams cone while their flowability and segregation resistance were determined by using the V-funnel apparatus.

2.3.1 L-box test

The L-box test was employed to determine the passing ability of the concrete through congested reinforcements. The test apparatus consisted of an 'L-shaped' rectangular section of a box with both vertical and horizontal sections separated by a movable gate having vertical reinforcing bars arranged directly behind the gate. The vertical section was filled with concrete and then the gate opened to allow concrete flow through the reinforcing bars into the horizontal section as presented in **Figure 2a**. The passing ability of concrete was taken as the proportion of the level concrete at the end of the horizontal section of the L-box to the remaining concrete in the vertical section when the flow stopped (EFNARC, 2002; Rao *et al.,* 2013 and Jin, 2002).

2.3.2 V-funnel test

The V-Funnel test was used to determine the filling-ability and segregation resistance of concrete. The 12-liter capacity V-funnel was filled to the brim with concrete, and the top of the funnel leveled with a trowel to remove excess concrete and without compaction. The trap door was opened within 10 sec and concrete was allowed to fall. The filling ability of the concrete was the time taken for complete discharge of concrete as illustrated in **Figure 2b.** The same process was repeated for segregation resistance (T_{5min} V-funnel Test) where the trap door was opened five minutes after the funnel was filled with concrete (EFNARC, 2002; Rao, *et al.,* 2013; Jin, 2002; De-Schutter, 2016; EN 12350-9, 2010).

Table 1: Mixture Proportioning

Sample	Mix Proportion	w/c	Cement (Kgm^{-3})	CCA (Kgm^{-3})	F.A (Kgm^{-3})	C.A (Kgm^{-3})	Admixture (Litres per 100kg of Cement)
1	C0	0.38	500	0	890	875	2
2		0.40	500	0	890	875	2
3	C5	0.38	475	25	890	875	2
4		0.40	475	25	890	875	2
5	C10	0.38	450	50	890	875	2
6		0.40	450	50	890	875	2
7	C15	0.38	425	75	890	875	2
8		0.40	425	75	890	875	2
9	C20	0.38	400	100	890	875	2
10		0.40	400	100	890	875	2
11	C0*	0.38	500	0	890	875	-
12		0.40	500	0	890	875	-

(a) L-box apparatus

(b) V-funnel apparatus

Figure 2: Passing ability test and flowability test using (a) L-box apparatus, and (b) V-funnel apparatus

2.3.3 Slump flow test

The slump flow test was employed to determine the horizontal free flow of SCC in the absence of any obstruction. The basic equipment in slump flow test is similar to that of the conventional slump test, but the measured parameters are quite different. A slump cone was filled with concrete sample, which collapsed upon the removal of the cone. Unlike the conventional test where the vertical slump is measured, the slump flow is a measure of the diameter of the spread of concrete on a horizontal plane. The flowability of the SCC was then determined as the average of the largest spread diameter d_{max} and the spread perpendicular to it d_{perp} (De-Schutter, 2016). The test is a general measure of the flowability of the SCC and the resistance and susceptibility of concrete to segregation. According to EN 12350-8 (2010), test results coupled with adequate practical experience on the behavior of SCC are required for reliable judgment on the characteristics of concrete that is well suited to practical field applications.

2.4 Mechanical Properties Determination

Concrete cylinder specimens of 100 mm diameter × 200 mm length were demoulded after 24 hours and cured by full immersion in water. The samples were subjected to compressive strengths at ages 7, 14, 21, 28 and 90 days, while the splitting tensile strength (Brazilian test) was tested at 28th day curing age only. The compressive strength and splitting tensile strengths tests were carried out in accordance with ASTM C39 (2005), using a digital 600 KN capacity universal testing machine as presented in **Figure 3**. The reported results of all the examinations were the average of three test results.

Figure 3: Compressive Strength Tests of Hardened Concrete Cylinders

3.0 RESULTS AND DISCUSSION

3.1 Physical and Chemical Properties of CCA

In **Figure 4**, it is noticed that the CCA used in the study was well graded, with coefficient of uniformity, C_u of 8.33; coefficient of curvature, C_c of 1.29; effective size of 0.09 mm; fineness modulus of 1.86; specific gravity of 3.15 and it had a Grayish -Purple color. Its chemical composition, as presented in **Table 2** categorized CCA as a class C pozzolanic material as it contains silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and Ferric oxide (Fe_2O_3) in the ash aggregated totaling 64.58 %, which was greater than 50 % (ASTM C 618-15, 2015).

3.2 Particle Size Analysis of Aggregates

The result of grain-size distribution as presented in **Figure 4**, confirmed that sharp river sand used as fine aggregate was uniformly graded with coefficient of uniformity, C_u of 2.29; coefficient of curvature, C_c of 1.51, effective size of 0.35 mm; fineness modulus of 2.38 and specific gravity of 2.65. The crushed granite stones used as coarse aggregate was uniformly graded with coefficient of uniformity, C_u of 1.38; coefficient of curvature, C_c of 1.14, effective size of 8 mm; fineness modulus of 2.91 and specific gravity of 2.77.

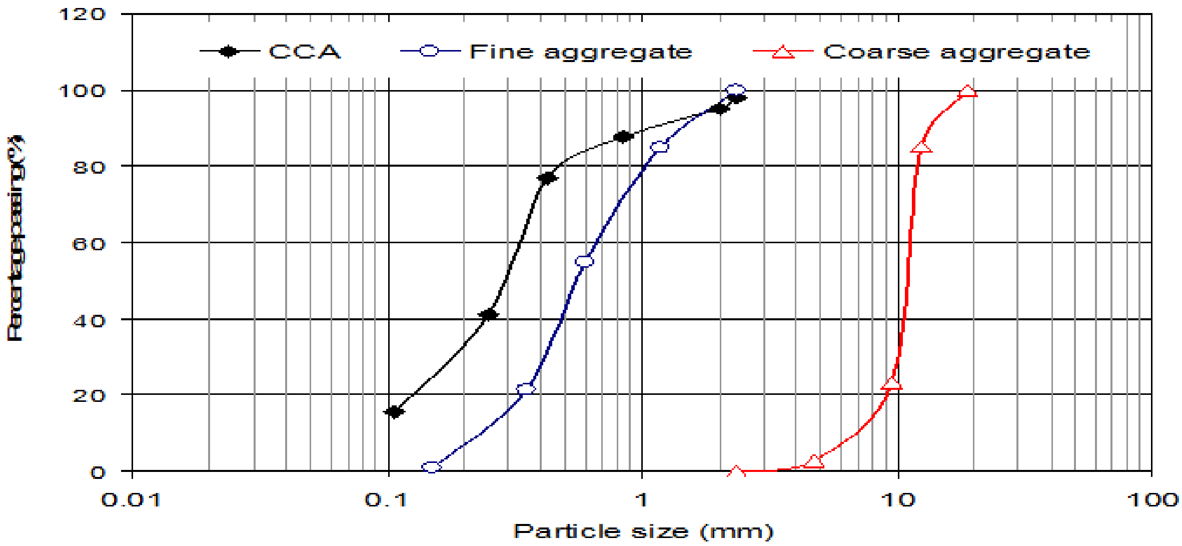

Figure 4: Particle size curve for CCA and Aggregate

Table 2: Physical and chemical properties of cement and CCA

Chemical Composition (%)	Cement	CCA
Calcium Oxide (CaO)	65.844	1.86
Magnesium Oxide (MgO)	2.346	1.68
Potassium Oxide (K_2O)	1.117	15.48
Sodium Oxide (Na_2O)	0.252	0.34
Manganese Oxide (MnO)	0.064	0.009
Aluminum Oxide (Al_2O_3)	4.422	4.92
Silicon Dioxide (SiO_2)	17.454	59.66
Zinc Oxide (ZnO)	-	0.49
Iron Monoxide (FeO)	-	3.96
Ferric Oxide (Fe_2O_3)	3.93	-
Titanium Oxide (TiO_2)	0.348	-
Phosphorus Pentoxide (P_2O_5)	0.068	-
Sulfur Trioxide (SO_3)	3.979	-
Chlorine (Cl)	0.012	-
Stronium Oxide (SrO)	0.072	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	25.806	64.58
PHYSICAL PROPERTIES		
Color	Ash	Greyish Purple
Specific Gravity	3.15	3.49
Combustion		Temperature was maintained between 625-650^{0}C for about 4-5 hours

3.3 Rheological Properties

The rheological properties of the CCA-SCC sample mixes reported according to EFNARC (2002) specifications are summarized in **Table 3**. It is evident in **Figure 5** that all samples produced from all the mixes except samples 11 and 12 containing neither CCA nor admixture met EFNARC (2002) requirements for flowability of SCC similar to the results of (Siddique, 2011; Mehdrad and Mohammad, 2015). The flowability of each pair CCA-blended cement SCC samples of the same CCA content was virtually comparable for the 0.38 and 0.40 w/b. On the other hand, the flowability of non-CCA-blended SCC samples was not recorded as the mixes were stiff and could not pass through the narrow opening of the V-funnel apparatus. Thus, indicating that the mixes without admixtures tend not to flow or possess filling ability characteristics. The EFNARC rheological requirement EFNARC (2002) limits for SCC are summarized in

Table 3. This could be attributed to the requirement of more uniform grading of aggregate, reduction in the maximum aggregate size and increase paste volume to reduce aggregate volume and inter-particle friction between aggregates. The non-CCA-blended SCC mixes were stiff as in the flowability test and could not pass through the narrow opening of the test apparatus, thus confirming that samples without admixtures neither possess flowability nor segregation resistance properties.

The passing ability and slump flow of the fresh SCC samples are presented in **Figure 6**. The passing ability of the SCC samples of 0.38 w/b control mix marginally passed EFNARC requirement, but 0.40 w/b control mix sufficiently satisfied the requirement. Moreover, the CCA content in the CCA-SCC samples below 15 % enhanced the passing ability at a cheaper cost of production than the control regardless of the w/b ratio. The passing ability of 15 % CCA-blended SCC was also comparable with the 0.38 w/b control mix. On the contrary, CCA content in excess of 15 % of any of the w/b was found unsuitable for CCA-SCC. It is particularly noteworthy that admixture is practically inevitable in the production of SCC as revealed by the stiff mix of the non-CCA-blended SCC without superplasticizers, which were unable to pass through the L-box gate as exhibited in the v-funnel tests.

The Slump flow tests carried out on all the mix samples as presented in **Figure 6** indicated that CCA replacements above 10 % required a higher dosage of admixture and/or water-binder ratio to meet the standard concrete horizontal flow requirement. Although, Samples 1 and 2 (Control Mix) had better slump flow properties than the CCA blended SCC mixes, the Slump flow of the control and CCA blended SCC mixes (Samples 1 to 10) were above 500 mm, which indicate that they have sufficient flow to pass through highly congested reinforcements. Samples 11 and 12 indicated 'True Slumps' when the slump cone was removed, but with slump flow of 0 and 300 mm respectively and these made them unsuitable to be classified as a self-compacting concrete. This further justifies the efficacy of superplasticizers in the rheological properties of SCC as exhibited in the L-box and v-funnel tests.

Table 3: Rheological properties of SCC

Sample	Flowability (sec)	Segregation Resistance (Sec)	Passing Ability (mm)	Slump Flow (mm)
EFNARC	6.0-12.0	Flowability +3	0.8 - 1.0	650 - 800

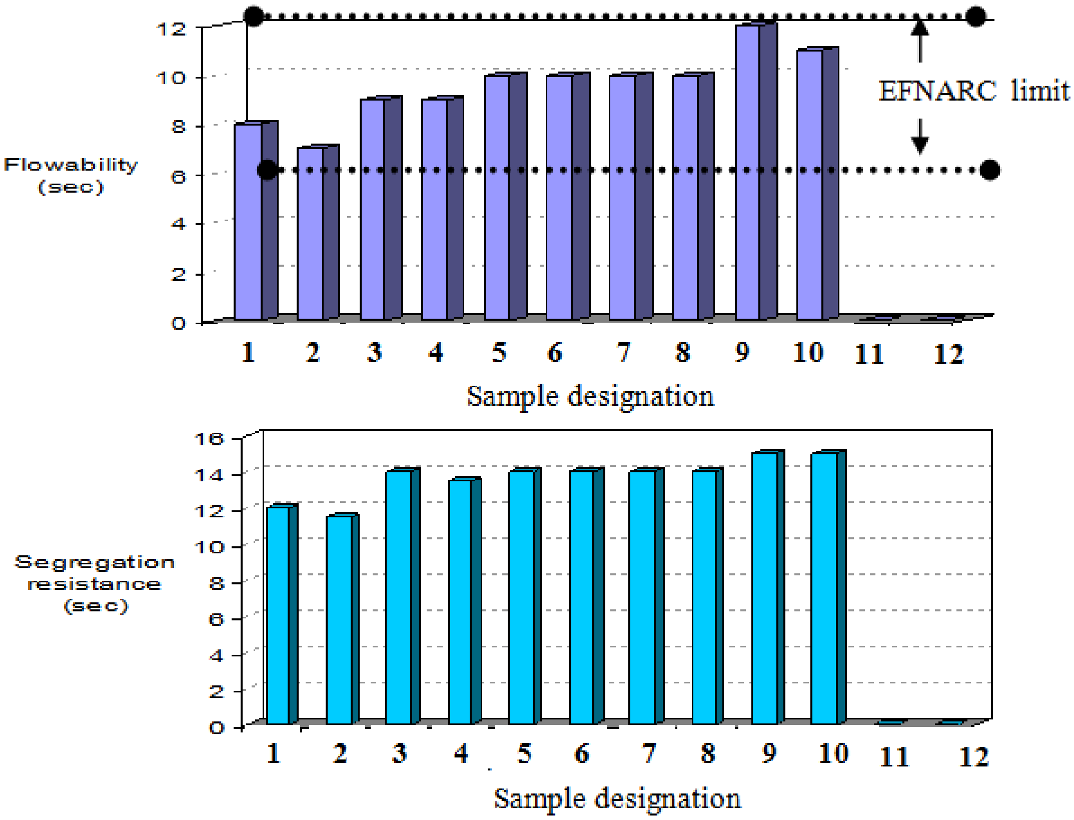

Figure 5: Flowability and segregation resistance of SCC samples

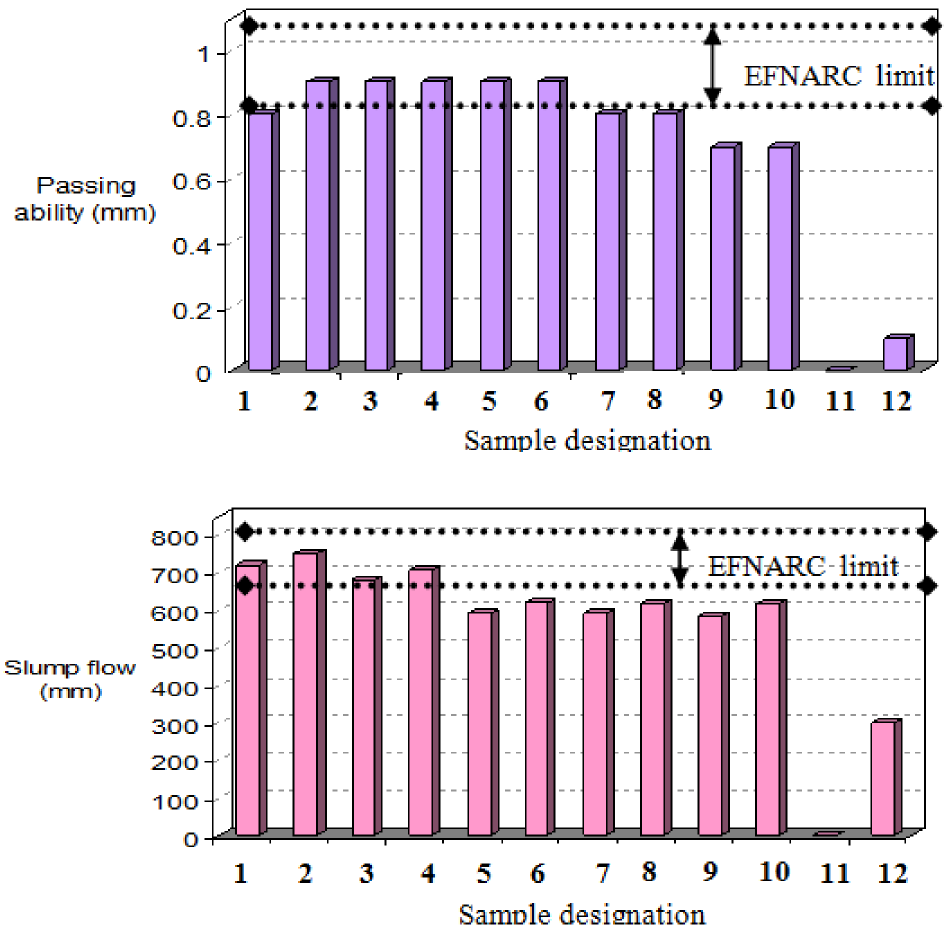

Figure 6: Passing ability and slump flow of SCC samples

However, CCA replacements above 15 % stiffens the concrete and influences the passing ability of the mixes negatively while CCA replacements above 10 % reduce slump flow slightly below the standard requirements. Examining the rheological properties of samples 11 and 12 the superplasticizers is seen to contribute positively to the rheological properties of SCC to meet EFNARC (2002) flow requirements. In line with the opinion of Yahia *et al*. (1999), that the inclusion of mineral admixtures such as fly ash and blast furnace slag and appropriate dosage of superplasticizer could increase the slump flow properties of SCC mixes without increasing its cost; CCA could enhance the rheology of SCC with adequate proportioning of the water-binder ratio and dosage of superplasticizers in the mix design.

3.4 Physical and Mechanical Properties of Hardened Concrete

3.4.1 Densities

Figure 7 showed that the densities of all the mixes increased with increased water-binder ratio. The increments in CCA content increased the densities of the SCC specimens up to 10 % replacement as in sample 6 of **Figure 7** with highest density of 2.77 Kgm^{-3} **(Figure 8)**. The densities subsequently decreased with increasing CCA contents above 10 % replacement. The densities of the mixtures 11 and 12 that were the lowest with 2.51 and 2.50 Kgm^{-3} respectively may be attributed to the high porosity of the hardened specimens.

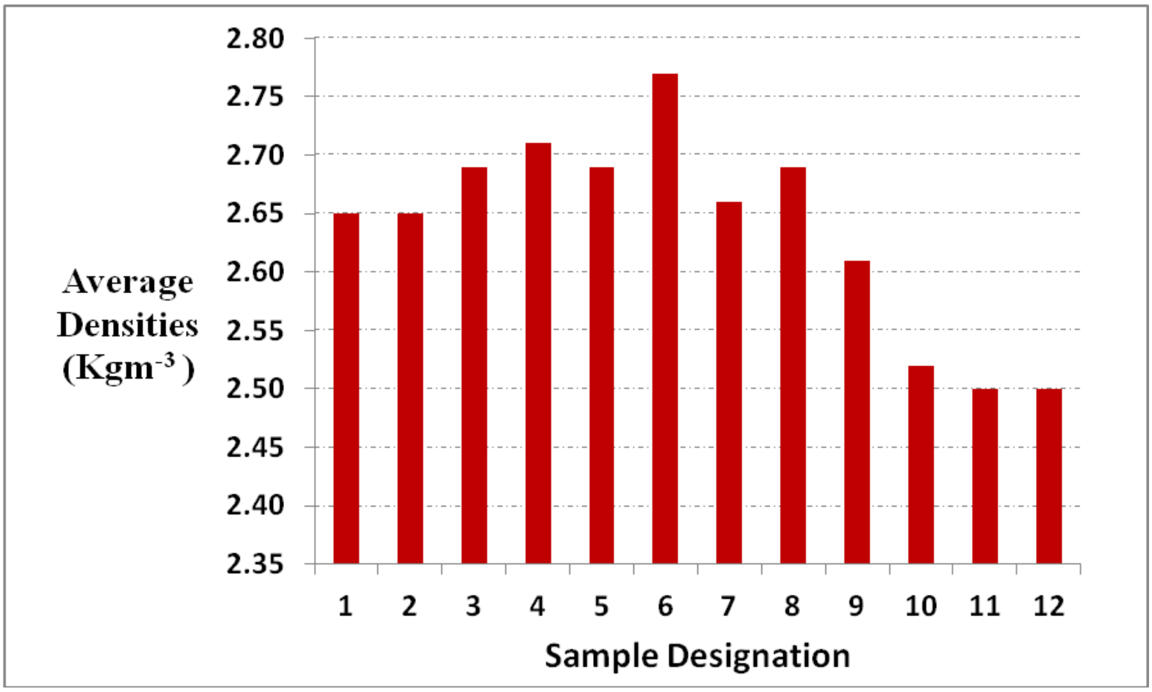

Figure 7: Average densities of hardened SCC cylinder specimens

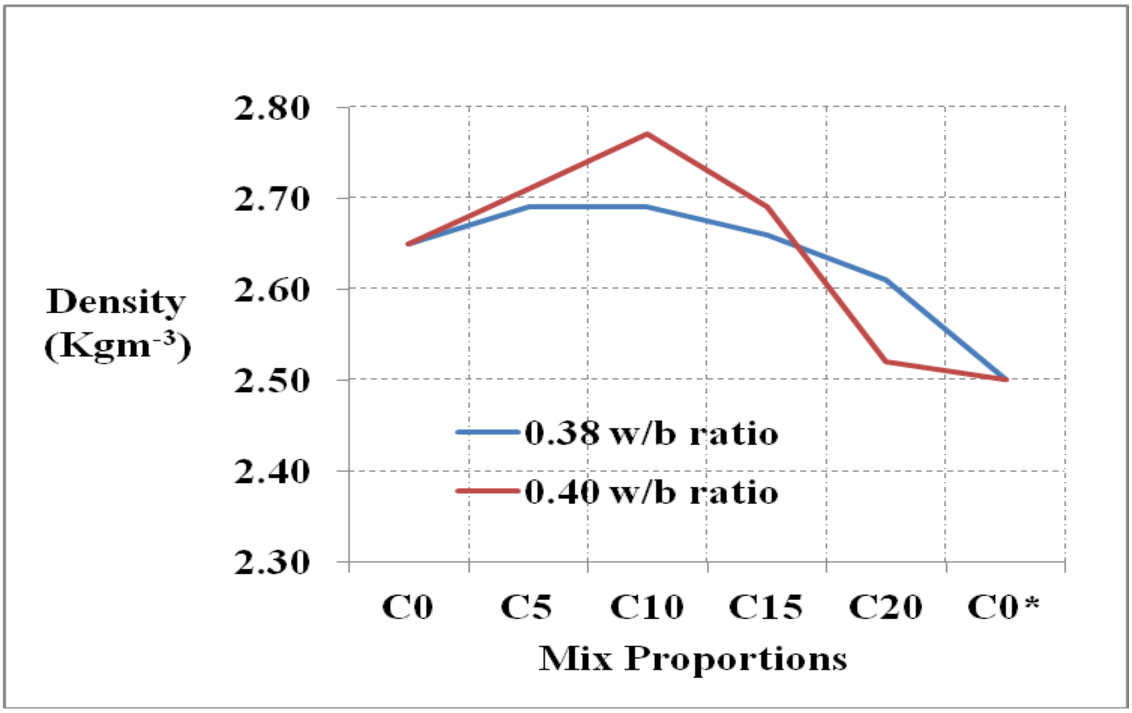

Figure 8: Effects of CCA on the densities of hardened SCC cylinder specimens

3.4.2 Compressive Strength

The strength-age relationship for all the mixtures is presented in **Figure 9**, while the effects of CCA on the SCC samples are presented in **Figure 10**. From the results, the 28th day compressive strengths of CCA blended SCC were lower than those of the control samples 1 and 2, but they had higher compressive strengths at 90th day with increased CCA content up to 10 % replacement and later decline steadily with higher replacements. The rate of strength gain in the mixes containing CCA was similar to those of the control mixes 1 and 2, especially the Sample 5, which eventually had the highest compressive strength of 23.55 Nmm^{-2}. SCC containing CCA gain more strength at 90-days within the range of 12.91 – 23.44 % of their compressive strength with an average compressive strength gain of 18.24 %. The compressive strength gain for the control SCC samples were within the range of 6.75 -12.94 %, with an average rate of 9.85 similar to the reports of Siddique (2011); where the rate of strength gain in SCC mixes containing fly ash ranged between 36.86 – 67.63 % of their 28th day compressive strength. However, due to pozzolanic reactions, mixes containing CCA gain strength rapidly after 28th day and tend to gain more beyond 90th day,while the control mixes 1 and 2 gained strength slowly after 28th day and may attain peak strength at 90th day. The compressive strengths of all the samples also increased with a reduced water-binder ratio.Those of mixtures 11 and 12 were surprisingly comparable to those of the control mixes that could be attributed to the properties of the concrete paste and coarse aggregate, which mostly influence the compressive strength of hardened concrete.

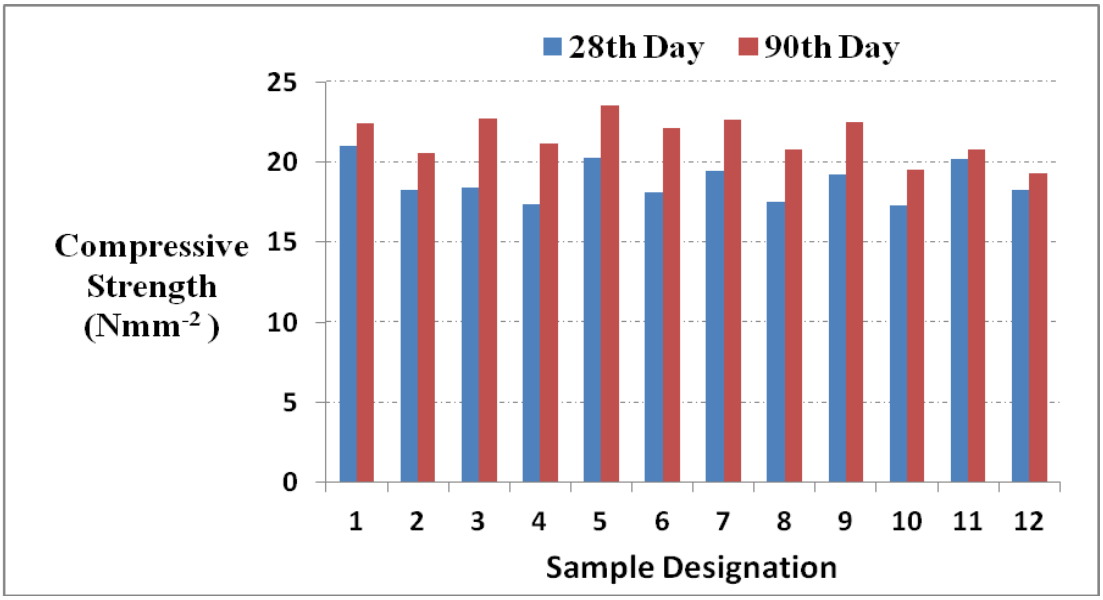

Figure 9: Compressive Strength of hardened SCC cylinder samples

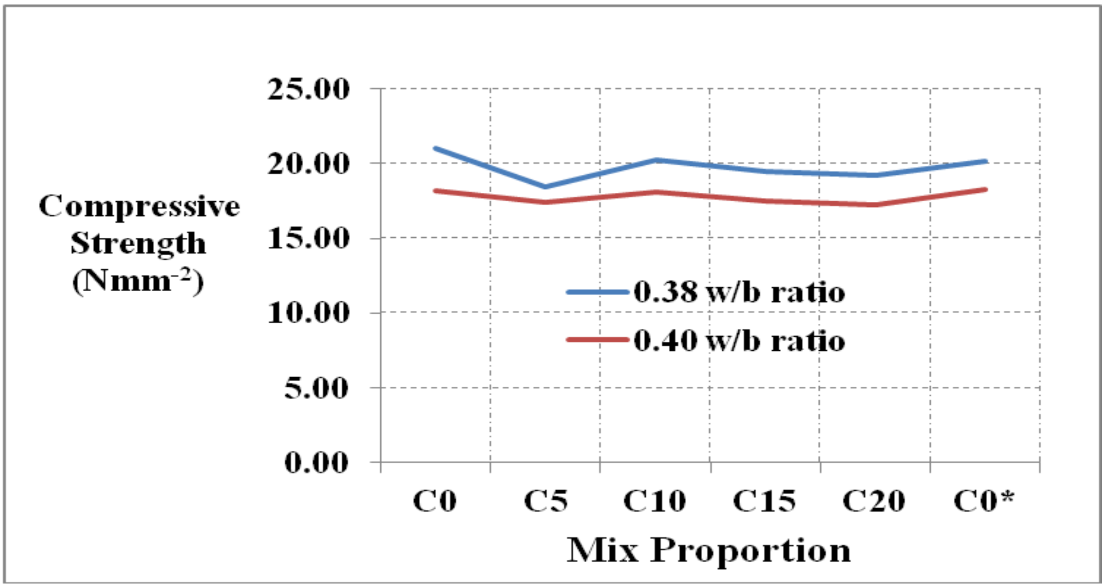

Figure 10: Effects of CCA on compressive strength of hardened SCC cylinder samples

3.4.3 Splitting Tensile Strength

The results of splitting tensile strengths are presented in **Figures 11 and 12.** From the Figures sample 1 had the highest splitting tensile strength of 2.57 Nmm^{-2} while sample 12 had the lowest splitting tensile strength of 1.64 Nmm^{-2}. The splitting tensile strengths of the CCA blended SCC ranged between 9.55 – 13.3 % of their 28 days cylinder compressive strength (f'_c) while the control samples ranged between 12.22 – 13.71 %; samples 11 and 12 had 8.32 and 8.97 % respectively. The splitting tensile strength of the control mixtures 1 and 2 seems to be slightly higher than those of conventional compacted concretes as reported by Olafusi and Olutoge (2012), while those of CCA blended SCC were lower than those of the control mixtures due to pozzolanic reactions. The mixtures 11 and 12, which had the lowest splitting tensile strength were probably due to the high porosity of the hardened unconsolidated concrete. This can be attributed to the absence of superplasticizer in the mixtures.

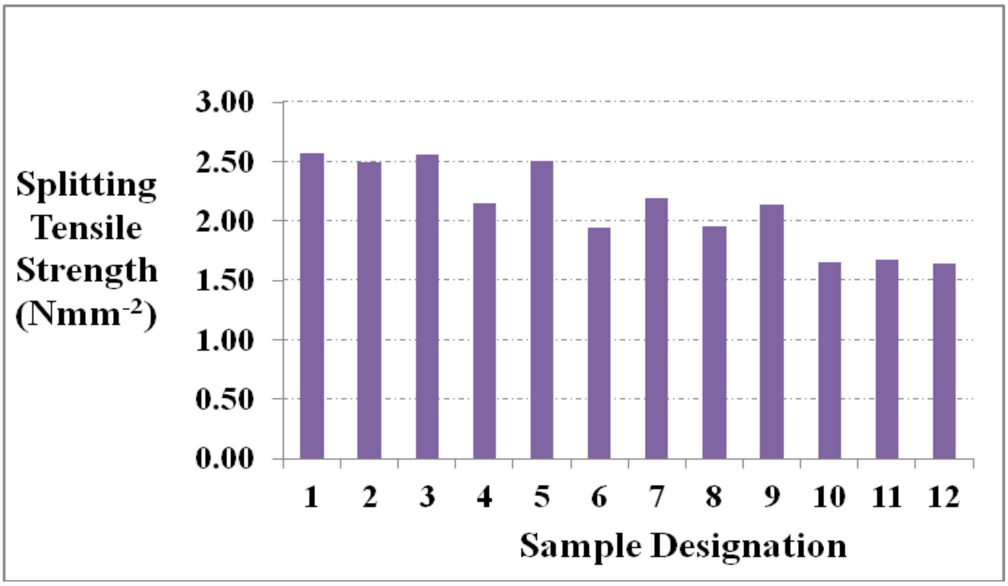

Figure 11: Splitting Tensile Strength of hardened SCC cylinder samples

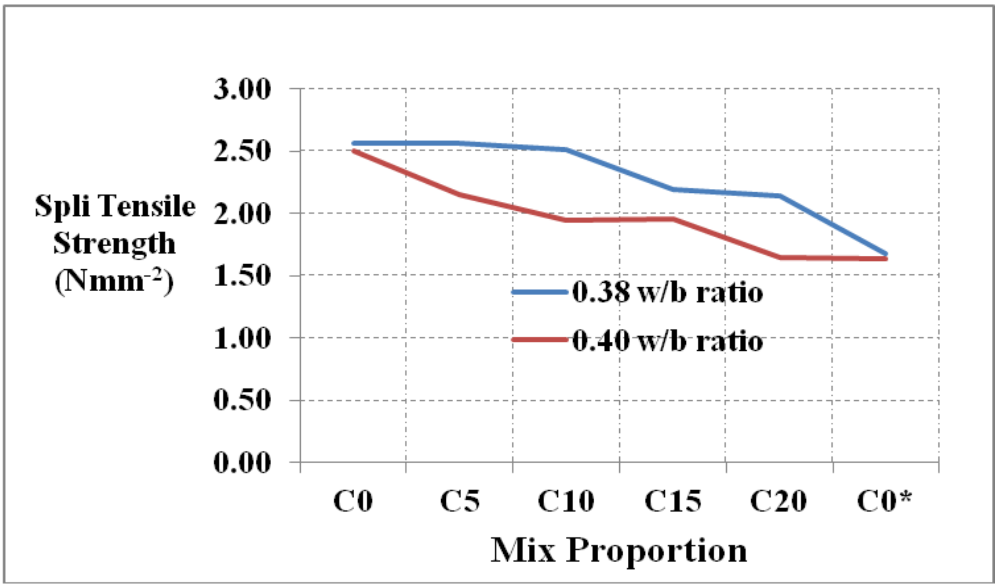

Figure 12: Effects of splitting Tensile Strength of hardened SCC cylinder sample

4.0 CONCLUSION

Based on the results above, the following conclusions are drawn;

1) All the mixes (including the ones containing CCA) meet EFNARC requirements for SCC flow properties except Samples 9, 10, 11 and 12 that indicated higher dosage of superplasticizer and/or water-binder ratio were needed to meet the flow requirements.
2) Superplasticizers play a very significant role in SCC.
3) Water-binder ratio influences the flow and strength properties of CCA blended SCC as much as it does in conventional concrete.
4) Densities of CCA blended SCC increased with age and water-binder ratio.
5) Compressive strengths of CCA blended SCC increased with age and reduced water-binder ratio.
6) Densities and compressive strengths of CCA blended SCC increased with increment in CCA content up to 10 % replacement.
7) The rate of strength gain in the mixes containing CCA is similar to those of the control mixes 1 and 2. However, due to pozzolanic reactions, mixes containing

CCA tend to gain more strength beyond 90 days while mixes without pozzolanic materials may have attained their peak strength at 90th day.

8) The high volume of cement content resulting in a higher SCC unit cost can be mitigated with the incorporation of pozzolanic materials in SCC production.

5.0 RECOMMENDATIONS

CCA replacements for OPC in SCC should not exceed 10 %, as higher replacements may require higher dosage of superplasticizer to satisfy EFNARC requirements. This may influence the hardened concrete properties negatively.

1) Further research should be carried out on the bond strength and durability characteristics of CCA blended SCC.

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