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MECHANICAL PROPERTIES OF SELF-COMPACTING CONCRETE WITH RECYCLED CONCRETE AGGREGATE, FLY ASH AND GRANULATED BLAST FURNACE SLAG

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ABSTRACT

In recent years, the demand for construction materials has grown tremendously, likewise the amount of construction and demolition waste, putting huge pressure on the environment. This has encouraged the use of recycled aggregate in concrete. This research aims to evaluate the mechanical properties of Self-Compacting Concrete with Recycled Concrete Aggregate (RCA) in varying percentages of replacement for Natural Coarse Aggregate (NCA). A total of 20 concrete mixtures were prepared and tested. Mixtures were divided into five different groups, with different volume fractions of Recycled Concrete Aggregate of 0%, 25%, 50%, 75% and 100% of NCA. The concrete is designed for a water-cement ratio of 0.38. Mixtures were designed with 50% of Portland cement substituted by a combination of class C fly ash and granulated blast furnace slag. The evaluation of concrete properties will include the workability of concrete using a slump test, compressive strength, and splitting tensile strength at the ages of 3, 14, and 28 days of curing. The results indicate that replacing the coarse aggregate with high percentages of RCA reduces the workability of the SCC. The addition of 25% FA + 25% SL in place of Portland cement increases the magnitude of the slump flow. The 28-day compressive strength of SCC with 50% SL is 5.3% less than the control. The inclusion of slag had a minimal effect on the 3, 14, and 28-day compressive strength. The optimum Recycled Concrete Aggregate content of 50% shall be used in Self-Compacting Concrete based on the findings of the results.

Keywords*: Self-Compacting Concrete, Recycled Concrete Aggregate, Compressive Strength, Fly Ash, Granulated Blast Furnace Slag*

INTRODUCTION

Concrete is the most commonly used construction material in civil engineering worldwide, and its usage is rising in parallel with construction activities. In 2017, China produced 5.51 billion tons of concrete, consuming about 5.0 billion tons of natural aggregates, which were non-renewable resources, and emitting carbon dioxide (CO_2) of about 0.83 billion tons (Guo et al., 2020). About 10% of the CO_2 in nature results from the transportation and production of concrete, thus leading to environmental pollution problems (Kuder et al., 2012). Recycled concrete aggregates (RCA), which are the most commonly studied recycled material in concrete production, must comprise a minimum of 90%, by mass, of Portland cement-based fragments and NA, according to some of the aforementioned specifications

On the other hand, development due to an increase in urbanisation around the world has caused construction and demolition waste (CDW) to increase rapidly and daily, which creates many environmental problems such as energy consumption, CO_2 emissions, noise pollution, traffic problems, agricultural land loss, and consumption of natural coarse and fine aggregates (Pani et al., 2020). Therefore, recycling CDW to produce recycled concrete aggregates (RCA) involves a complete or partial replacement of natural coarse aggregate (NCA) in the concrete industry, which has become an urgent necessity to protect the environment and also to reduce non-renewable natural resource consumption (Ahmed et al., 2023).

The global total production of 40 billion tons indicates the extensive development projects taking place worldwide. As suitable land for landfills becomes scarce and global demand for aggregate reaches an enormous 40 billion tons annually, finding ways to reuse construction and demolition (C&D) waste is becoming increasingly important due to legislation, as it is more affordable and readily available. However, significant research and development are needed to sustainably utilise alternative materials in the production of concrete containing recycled aggregate.

In recent years, in national construction practice, self-compacting concrete (SCC) has been actively applied to address different issues (Abreu et al., 2018; Kou and Poon, 2009). SCC is a viscous mixture suitable for casting intricate structures and structures with congested reinforcement, with slight or without vibration, while maintaining a consistent flow free from segregation and bleeding (Falmata et al., 2020). Self-compacting concrete was initiated by Okomora (1986), and the model of SCC was developed in 1988 at Tokyo University. The objective was to produce a durable concrete structure by improving quality in the construction industry. Using SCC allows for an increase in working efficiency and enhances the quality of concrete and reinforced concrete structures and precast elements (Ahmed et al., 2023).

There has been a dramatic decline in good-quality aggregate available for construction use. Worldwide aggregate use is estimated to be ten to eleven billion tons each year. Of this, approximately eight billion tons of aggregate (sand, gravel, and crushed rock) is being used in Portland Cement Concrete every year (Naik 2005, Mehta 2001). Moreover, there is a critical shortage of natural aggregate and an increasing amount of demolished concrete. It is estimated that 150 million tons of concrete waste are produced in the United States annually (Salem 2003). Concrete structures that are designed to have service lives of at least 50 years have to be demolished after 20 or 30 years because of early deterioration. In 2005, the American Society of Civil Engineers reported that US infrastructure was in poor condition with an estimated repair cost of $1.6 trillion over five years. The environmental impact of waste concrete is significant.

Construction and demolition (C&D) waste makes up a large portion of all generated solid waste. In 1980, the Environmental Resources Limited in the European Communities (EEC) estimated that 80 million tons of demolition waste were produced each year. This number is expected to double by 2000, and triple by 2020. The recycling of construction and demolition wastes, such as RCA, resolves the disposal problem, reduces landfill space, conserves natural resources, decreases transport costs, diminishes environmental pollution, and protects ecological balance.

Moreover, SCC prepared with recycled concrete aggregate has not been extensively studied yet (Manzi et al., 2020). Hence, a need to fully understand the mechanical behaviour of self-compacting concrete with recycled concrete aggregate.

Hence, a need to understand the mechanical properties of self-compacting concrete with recycled concrete aggregate. This research is intended to understand the optimum fraction of recycled concrete aggregate in self-compacting concrete, thereby providing fundamental information for its effective use in SCC with class C fly ash and granulated blast furnace slag. Therefore, this research aimed to assess the properties of self-compacting concrete that combines both supplementary cementitious materials and recycled concrete aggregate.

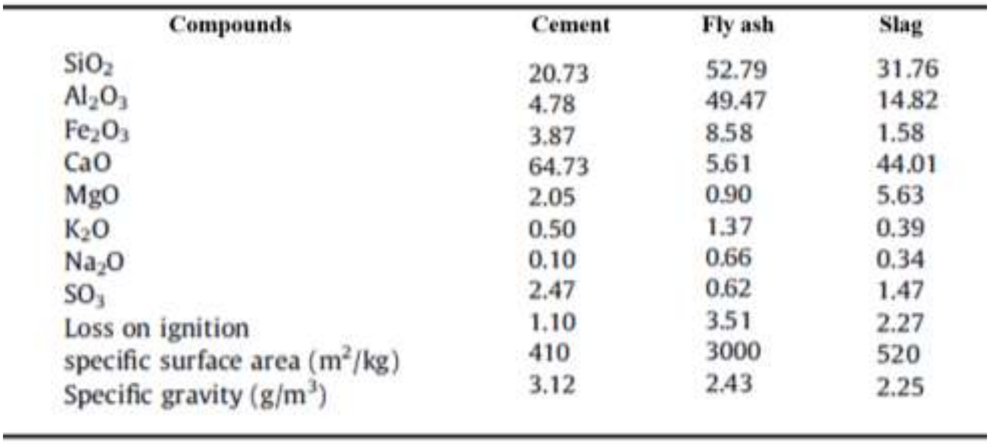
MATERIALS AND METHODS

Materials

Cement and Supplementary Cementing Materials (SCMs)

An ordinary Portland Cement of CEM 1 with 42.5 MPa strength and a specific gravity of 3.15 was used to produce the concrete mixtures. The chemical composition of the cement and SCMs utilised is presented in Table 1. SCMs such as ground granulated blast furnace slag (SL), class C fly-ash (FA) were also used in mixtures other than the control mixes. The SCMs, FA and SL have specific gravity values of 2.6 and 2.94, respectively. The FA and SL have a surface area of 350 m^2/kg and 500 m^2/kg, respectively. A highly efficient new generation of polycarboxylic-based High-range Water Reducer Admixture (HRWRA) having a density of 1.1 g/cm^3 was used in the mixtures. This type of HRWRA contains a viscosity-modifying agent that enhances concrete viscosity. The recommended dosage for the HRWRA varies between 200 and 780 mL/100 kg of the cementitious materials (Fantous and Yahia, 2020).

Table 1. Chemical Composition of OPC, fly ash, and slag



Compounds	Cement	Fly ash	Slag
SiO_2	20.73	52.79	31.76
Al_2O_3	4.78	49.47	14.82
Fe_2O_3	3.87	8.58	1.58
CaO	64.73	5.61	44.01
MgO	2.05	0.90	5.63
K_2O	0.50	1.37	0.39
Na_2O	0.10	0.66	0.34
SO_3	2.47	0.62	1.47
Loss on ignition	1.10	3.51	2.27
specific surface area (m^2/kg)	410	3000	520
Specific gravity (g/m^3)	3.12	2.43	2.25

Fine, Coarse Aggregates and Recycled Concrete Aggregate (RCA)

Natural river sand was used for the mixtures with relative density (SSD), water absorption and fineness modulus of 2.65 kg/m^3, 1.15% and 3.17, respectively. A well-graded 10 mm aggregate with relative density (SSD) and water absorption value of 2.66 kg/m^3 and 1.0% respectively, was used as coarse aggregate in accordance with BS 882 (1992). The RCA materials were sieved and separated into different sieve sizes and then recombined in proportions equal to the coarse aggregate gradation. The relative specific gravity of RCA was 2.58.

Mixture Proportions and Specimen Preparation

A total of 20 concrete mixtures were prepared and tested, five of which are designed as control mixtures made with 100% Portland cement and different RCA content (0, 25, 50, 75, and 100%). The w/cm ratio was fixed for all mixtures at 0.38. The remaining mixtures were divided into 5 groups; the first of which has no RCA, the RCA replaced the coarse aggregate by 25, 50, 75, and 100% in the second, third, fourth, and fifth groups, respectively. All mixtures were proportioned to achieve acceptable flowability (i.e. slump flow value between 500 ± 10 to 750 ± 10 mm as well as high resistance to segregation and bleeding). The ratio of the coarse aggregate to fine aggregate (CA/FA) was kept constant for all mixtures. The HRWRA for all mixtures was added during the mixing directly to freshly mixed concrete in the concrete mixer at the end of the batching cycle for best results. To optimise the super-plasticising effect, after the addition of the HRWRA, the combined materials were mixed for nearly 100 revolutions in the concrete mixer according to the guidelines of the HRWRA manufacturer. The slump flow is measured immediately after the 100 revolutions are reached. Table 2 shows the actual dosages used in the design

Table 2. Proportions of Concrete Mixtures

Concrete Mixes	% of SCM	% of RCA	Cementitious Materials (kg/m^3)			Water (kg/m^3)	Aggregate (kg/m^3)			SP (Ml/m^3)
			C	FA	SL		RCA	CA	FA	
C_1	**Control**	0%	375	0	0	143	0	865	880	592
C_2	50% FA	0%	187.5	187.5	0	143	0	865	880	632

C_3	50% SL	0%	187.5	0	187.5	143	0	865	880	796
C_4	25% FA + 25% SL	0%	187.5	93.75	93.75	143	0	865	880	756
C_5	**Control 25%**	25%	375	0	0	143	216	649	880	671
C_6	50% FA	25%	187.5	187.5	0	143	216	649	880	592
C_7	50% SL	25%	187.5	0	187.5	143	216	649	880	717
C_8	25% FA + 25% SL	25%	187.5	93.75	93.75	143	216	649	880	790
C_9	**Control 50%**	50%	375	0	0	143	432.5	432.5	880	677
C_{10}	50% FA	50%	187.5	187.5	0	143	432.5	432.5	880	796
C_{11}	50% SL	50%	187.5	0	187.5	143	432.5	432.5	880	716
C_{12}	25% FA + 25% SL	50%	187.5	93.75	93.75	143	432.5	432.5	880	890
C_{13}	**Control 75%**	75%	375	0	0	143	648.75	216.25	880	720
C_{14}	50% FA	75%	187.5	187.5	0	143	648.75	216.25	880	870
C_{15}	50% SL	75%	187.5	0	187.5	143	648.75	216.25	880	845
C_{16}	25% FA + 25% SL	75%	187.5	93.75	93.75	143	648.75	216.25	880	921
C_{17}	**Control 100%**	100%	375	0	0	143	865	0	880	847
C_{18}	50% FA	100%	187.5	187.5	0	143	865	0	880	923
C_{19}	50% SL	100%	187.5	0	187.5	143	865	0	880	884
C_{20}	25% FA + 25% SL	100%	187.5	93.75	93.75	143	865	0	880	1142

Test on Fresh Concrete

The properties of fresh concrete, such as flowability, passing ability and segregation resistance of all prepared mixtures, were evaluated. The flowability of SCC mixtures was measured using the slump-flow and T_{50} tests. Concrete deformability and filling capacity were measured using the slump-flow and T_{50} tests, while the J-Ring and concrete resistance to segregation were evaluated using the segregation index test. The slump flow test was performed as per ASTM C1611, where an inverted slump cone was filled with SCC without vibration. The cone was then lifted, and the measure of the spread of concrete was recorded. The slump flow value was calculated as the average of two perpendicular diameters of the concrete spread after lifting the cone. Additionally, the T_{50} test was conducted to measure the rate of concrete deformability, which consists of measuring the time needed for the SCC mix to reach a 500 mm spread during the slump flow test. A slump flow value that ranges between 500 and 750 mm and a value of T_{50} less than 7 s are acceptable limits for the design of SCC concrete mixtures (EFNARC 2005). Figure 1 shows a typical slump flow and T_{50} tests. Similar to the slump flow test, the J-Ring test consists of measuring the average diameter of the concrete spread after lifting the inverted concrete cone and the time needed for the concrete to reach a circle of a 50 cm diameter was recorded as the T_{50} value with the J-Ring.

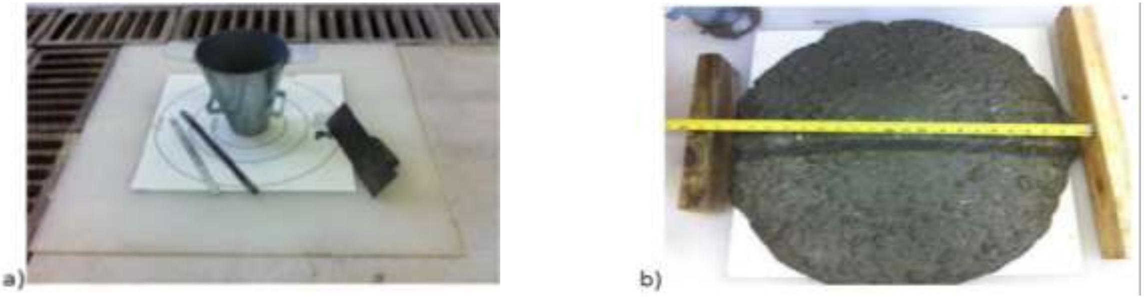


Figure 1 (a) Slump flow test set-up, (b) measuring slump flow of SCC mixture

Figure 2 shows the J-ring test set-up and a typical concrete spread using the J-Ring.

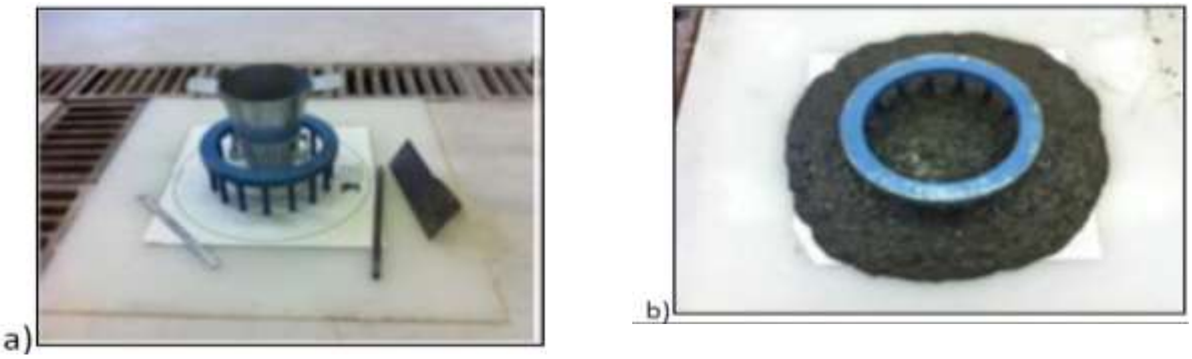


Figure 2 (a) J-ring set-up and (b) typical spread using the J ring

Hardened Properties Test

The hardened properties test on the concrete comprises;

Compressive Strength Test

The compressive strength test on 100 x 100 mm cubes was conducted on a 3000 kN capacity universal testing machine in accordance with BS EN12390-3 (2009) as depicted in Figure 3. The test was conducted at the ages of 7 and 28 days. Three (3) samples for each batch were measured and the average value was calculated to evaluate the compressive strength by using Equation 1

$$F_C = {}^{F}/_{A_C} \qquad \text{Eqn (1)}$$

Where; F_C is the compressive strength (N/mm^2 or MPa), F is the compressive force at failure (N), and A_C is the specimen cross-sectional area (mm^2).

Splitting Tensile Test

Splitting tensile test on 100 x 200 mm cylinders was carried out using the NL Compression machine with a capacity of 3000 kN in accordance with the specification of ASTM C496/C496M-11 (2002). The maximum fracture load was recorded directly from the machine and computed using Equation 2 below;

$$F_{ct} = {}^{2F}/_{\pi L D} \qquad \text{Eqn (2)}$$

Where; F_{ct} is the splitting tensile strength in MPa, F is the maximum load in Newton, L is the height of the sample in mm, and D is the diameter of the specimen in mm.

RESULTS AND DISCUSSIONS

Fresh Concrete

The fresh properties of all concrete mixtures were measured to ensure that the concrete is flowable, stable, and meets certain requirements from current standards to be classified as SCC. They were assessed using the slump flow, T_{50} tests with and without the J-Ring, and the segregation index test. In general, a slump flow value between 500 and 750 mm and a value of T_{50}\7s are considered acceptable for SCC design (EFNARC 2005).

Table 3 shows the fresh properties of all concrete mixtures. It has been observed that fly ash and slag increase the workability of concrete for all mixtures, including those incorporating RCA. $C_{75FA25SL25}$, $C_{100FA50}$, and $C_{100FA25SL25}$ required the highest dosage of HRWRA to achieve the targeted slump flow values (543, 572, and 602 mm). This indicates that replacing the coarse aggregate with high percentages of RCA reduces the workability of the SCC. Figure 3 shows the slump flow values and the slump flow with J-Ring for all concrete mixtures. Almost all of the concrete mixtures achieved the minimum requirements for self-consolidating concrete. The slump flow values change with the incorporation of RCA into the concrete mixtures. The substitution of coarse aggregate by 25, 50, and 100% RCA decreased the hang stream regard by 0.8, 5.8, and 9.9%, respectively, while it was essentially the same for the 75% RCA substitution mixture in light of high flowability in the concrete mixture compared with different substitutions. The use of (25% FA + 25% SL) instead of cement increased the magnitudes of the slump flow values in almost every mixture group.

Table 3 shows that the use of 50% FA in place of cement increased the slump flow in the mixtures with 75, and 100% RCA replacement, whereas the slump flow values were almost identical for the remaining design mixes with 0, 25, and 50% RCA replacement. This is presumably because of high utilisation of HRWRA on account of high-water absorption due to high RCA content. Moreover, the use of 50% SL instead of cement did not have any significant change on the slump flow values in the different mixture groups. The lowest slump flow value was monitored when the coarse aggregate was replaced with 75% RCA and the cement by (25% FA + 25% S), where the flowability of concrete very nearly achieves segregation. Furthermore, binary mixtures made with a high content of FA and SL required a greater amount of HRWRA than that of the control mixture by 6.8, 34.5, and 27.7% for the cases of 25% FA, 25% SL, and (25% FA + 25% SL) with no RCA, respectively.

Table 3 Properties of Fresh Concrete Mixtures

Concrete Mixes	**Segregation Ratio**	**Fresh Properties**			
		Slump Flow (mm)	**T_{50} (sec)**	**J-Ring (mm)**	**SP ml/m^3**
C_0	0-1	607	4	557	592
C_{0FA50}	0	558	3	521	632
C_{0SL50}	0	585	4	543	796
$C_{0FA25SL25}$	0	621	2	574	756
C_{25}	0	602	4	562	671
C_{25FA50}	0-1	558	5	512	592
C_{25SL50}	0	576	6	524	717
$C_{25FA25SL25}$	0	597	5	552	790
C_{50}	0	572	4	535	677
C_{50FA50}	0-1	555	3	506	796
C_{50SL50}	0-1	586	4	543	716
$C_{50FA25SL25}$	0	624	2	587	890
C_{75}	0	610	3	570	720
C_{75FA50}	0-1	579	2	525	870
C_{75SL50}	0	588	4	540	845
$C_{75FA25SL25}$	0-2	543	5	497	921
C_{100}	1	547	2	504	847
$C_{100FA50}$	0	572	2	527	923
$C_{100SL50}$	0-2	585	7	538	884
$C_{100FA25SL25}$	0-1	602	3	567	1142

The amount of HRWRA needed for the control mixtures of the five groups of mixtures (0, 25, 50, 75, and 100% RCA) increased by 13.3, 14.4, 21.6, and 43.1%, respectively. Additionally, the same trend was observed for the mixtures incorporating FA and/or SL, which indicates that replacing the CA with RCA required greater amounts of HRWRA. The amount of HRWRA required for mix C_0 (0% RCA) was 69.9% of that of the amount required for mix C_{100} (100% RCA), which shows the adverse effect that replacing the CA by RCA has on the flowability of the SCC mixes.

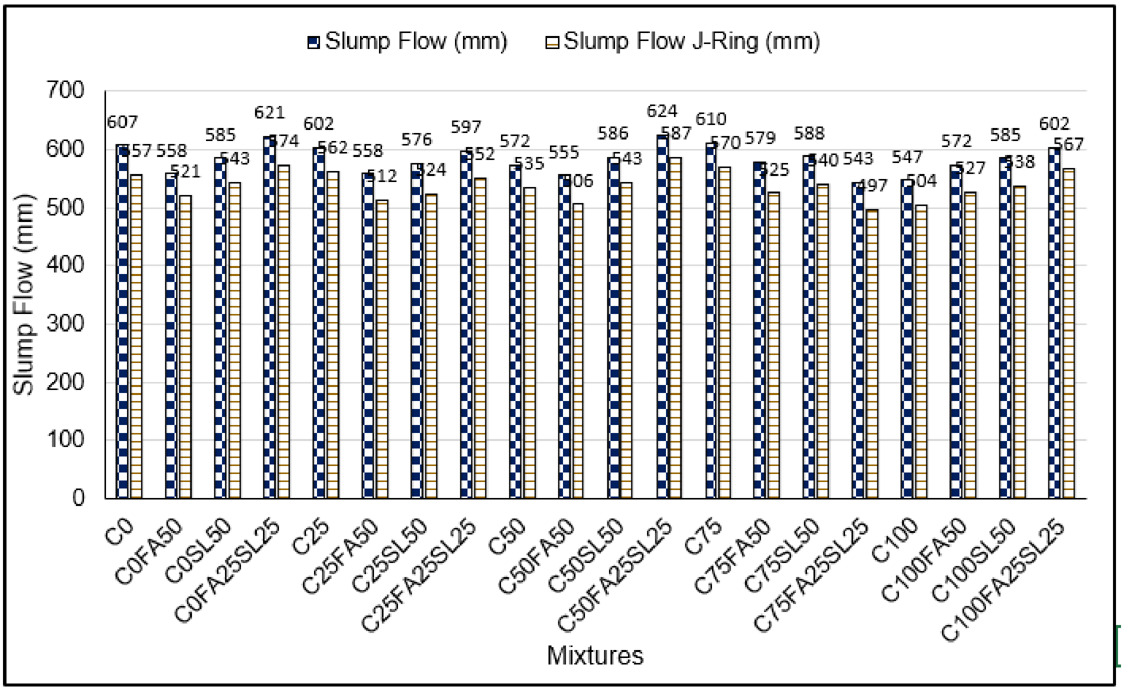


Figure 3 Slump Flow of SCC Concrete Mixtures

Additionally, all of the SCC mixtures showed high deformability, indicated by the high slump flow values and the smaller T_{50} test values. The mixtures also showed moderate viscosity because the HRWRA used in this study contains a viscosity-modifying agent in its production, and using high dosages of such an admixture to achieve a slump flow value higher than 500 mm enhances concrete viscosity. Table 3 shows that the largest amount of HRWA of 1142 ml/m^3 was used for the case of 100% RCA using (25% FA + 25% SL). This is due to the high absorption of water in RCA compared to the CA. It is well known that there is very limited data related to the amount of HRWRA needed for any concrete mix. Figure 3 shows a typical slump flow and a slump flow with the J-ring for the mixtures tested. All mixtures have exceeded the minimum requirements for the formation of SCC (slump flow values between 500 and 750 mm and $T_{50} < 7$ seconds).

Hardened Properties of SCC Concrete with Fly Ash and Slag

The properties considered in this section are compressive strength and splitting tensile strength.

Compressive Strength of SCC Concrete with Fly Ash and Slag

Figures 4 to 8 summarise the effect of replacing the CA with 0, 25, 50, 75, and 100% RCA on the compressive strength. It is clear from the results that as the percentage of RCA increases, the compressive strength decreases for all different combinations of CA and RCA. The addition of FA and SL to mixtures has resulted in the reduction of the compressive strength at 3, 14 and 28 days. However, the decrease in the compressive strength of the mixtures containing FA was more than that of those containing SL or FA and SL. The 28-day compressive strength for Mixes C_{0FA50}, C_{0SL50}, and $C_{0FA25SL25}$ was less than that of C_0 (control mix) by 18.32%, 5.3%, and 15.6%, respectively, as shown in Figure 4. The same trend was observed for mixes containing 25, 50, 75, and 100% RCA as depicted in Figures 5, 6, 7 and 8, respectively. The inclusion of slag to mixtures had a minimal effect on the 3, 14, and 28-day compressive strength.

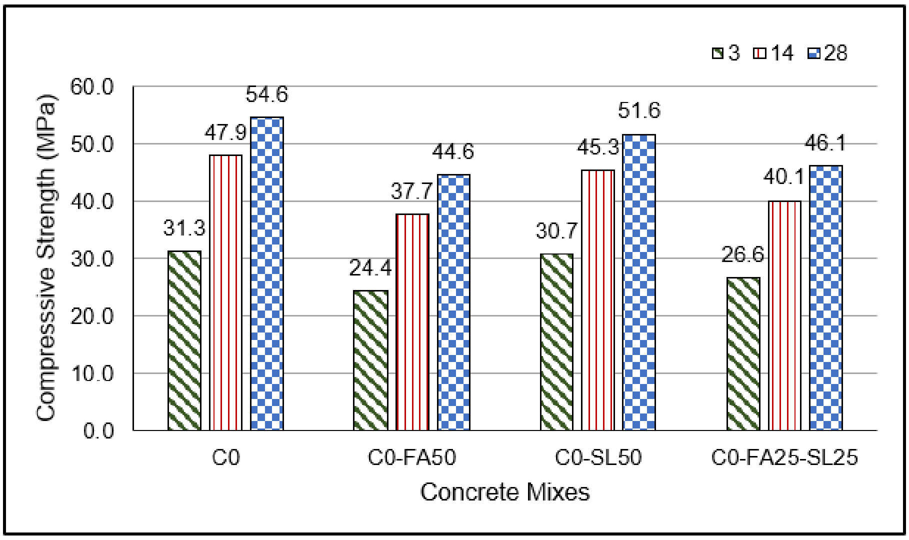


Figure 4: SCC Concrete with 0% RCA

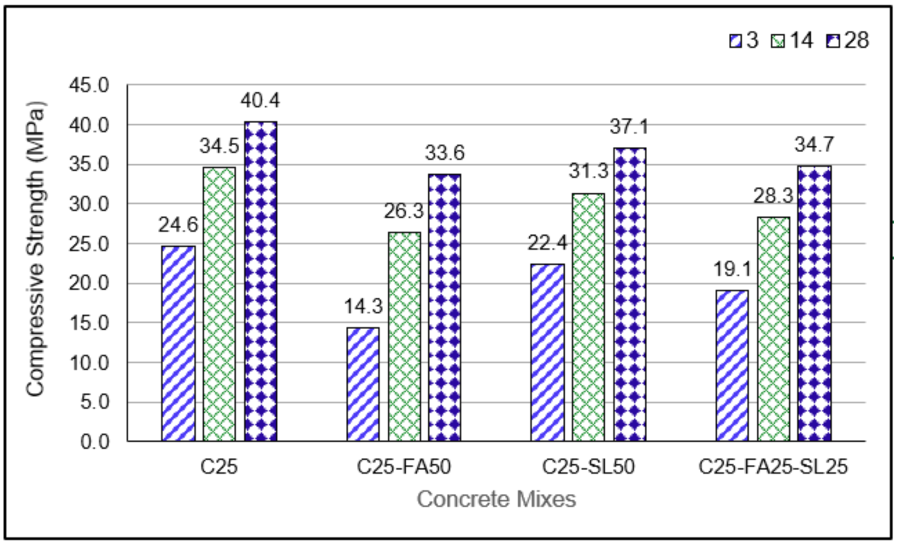


Figure 5: SCC Concrete with 25% RCA

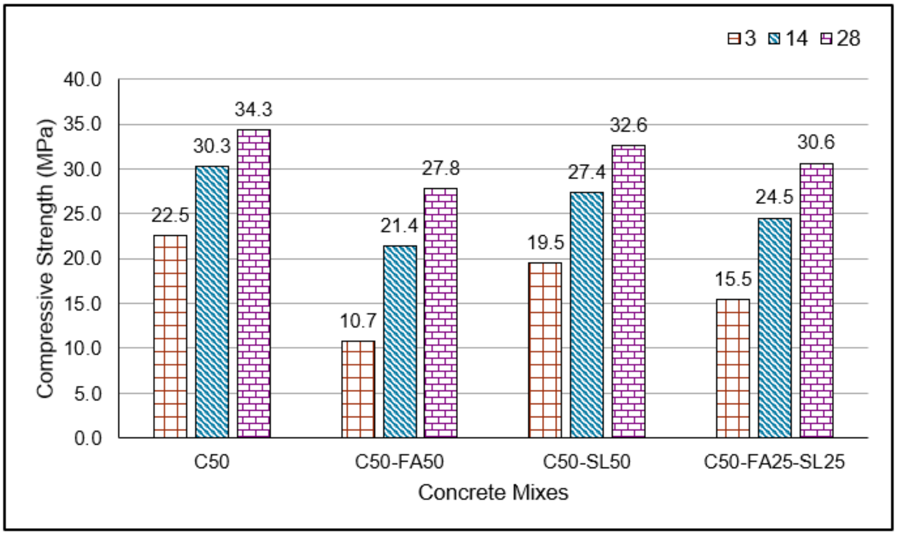


Figure 6: SCC Concrete with 50% RCA

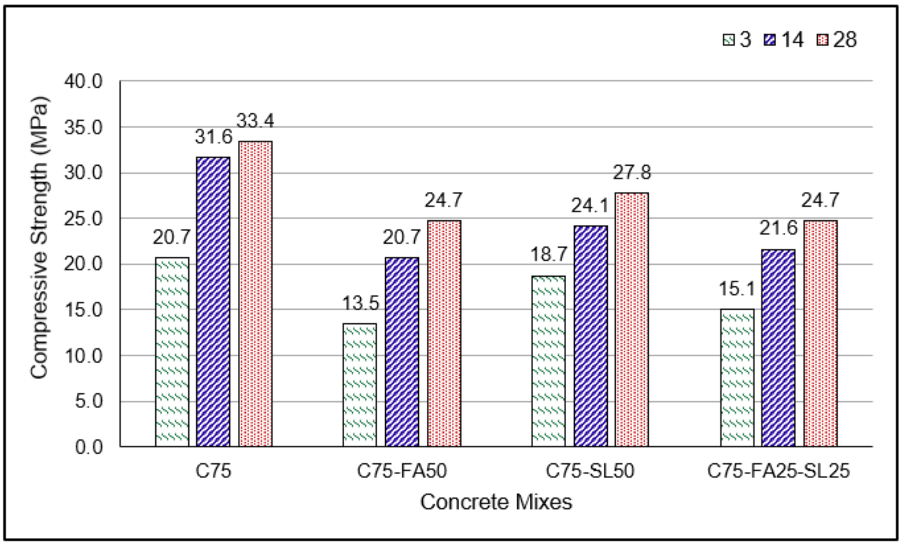


Figure 7: SCC Concrete with 75% RCA

The 3-day compressive strength was less than that of the control mixture by 2.55%, where the 14 and 28-day compressive strengths were less by 5.83% and 5.3%, respectively. However, the compressive strengths of the mixes containing fly ash were the least among all mixes, where the reduction was 22.61%, 21.7%, and 18.32% compared to the control mix (0% RCA) after 3, 14, and 28 days, respectively. A similar trend was observed for the cases of 25, 50, 75, and 100% RCA for the 3, 14, and 28-day mixes. Mixes with both 25% fly ash and 25% slag had an intermediate strength between those with 50% fly ash only and 50 % slag only, as shown in Figure 4 – 8.

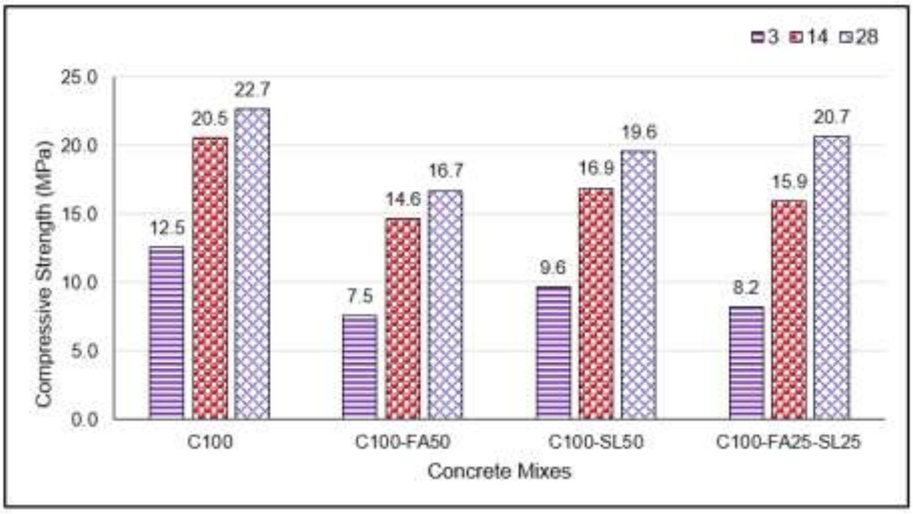


Figure 8: SCC Concrete with 100% RCA

3.2.2 Splitting Tensile Strength of SCC Concrete with Fly Ash and Slag

Figure 9 shows the split tensile strength of all tested mixtures at 28 days. The results are configured to illustrate the effect of replacing the CA by different percentages of RCA. As the RCA content increased from 0 to 100% the split tensile strength of all mixtures decreased accordingly. The maximum tensile strength recorded was 6.2 MPa which corresponds to the control mixture C_0 of 100% cement and 0% RCA, while the minimum recorded was 1.8 MPa, which corresponds to $C_{100FA50}$ of 50% fly ash and 100% RCA. Replacing the cement with 50% slag increased the tensile strength for all different RCA contents compared to replacing it with 50% fly ash and 25% fly ash and 25% slag. In general, it is observed that the tensile strength of SCC mixture is around 10 -15% of compressive strength.

The tensile strength of the SCC concrete with FA and SL at various fraction of RCA is illustrated in Figure 10. It can be observed that the tensile strength decreased with increment in the fraction of RCA from 6.2 MPa to 2.9 MPa which corresponds to C_0 to C_{100}. This can be attributed to the porous, mortar-coated surface of the aggregate, which weakens the bond with new paste and lowers the density of the concrete. However, the reduction in the tensile strength can be mitigated through careful aggregate selection, treatment, or the addition of supplementary cementitious materials can improve performance over long curing times.

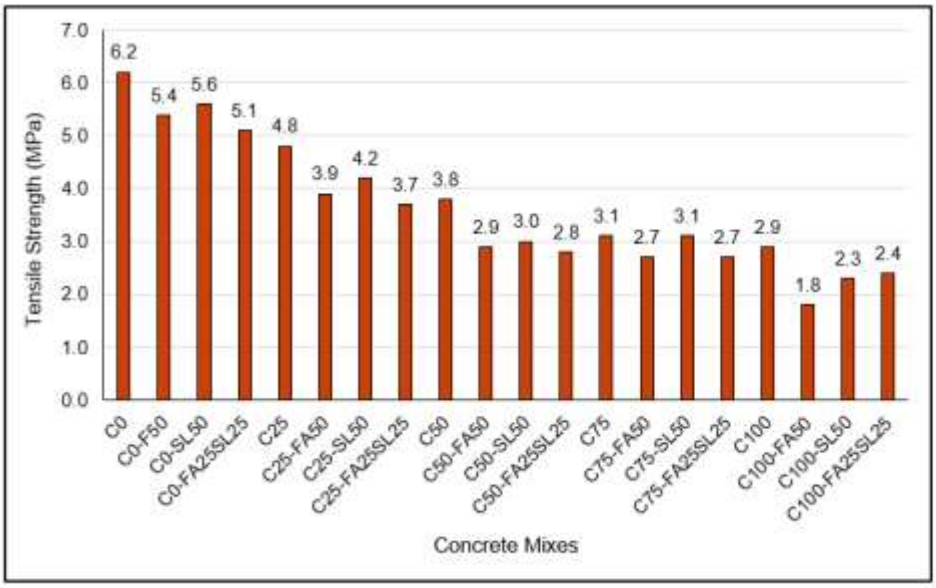


Figure 9: Tensile Strength of SCC Concrete

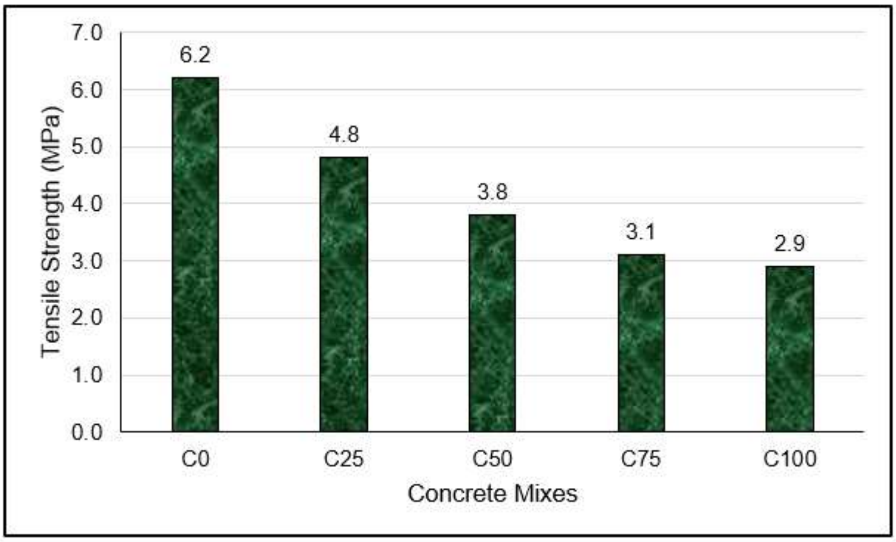


Figure 10: Tensile Strength of SCC Concrete with % RCA

CONCLUSION

This paper highlights the mechanical properties of Self-Compacting Concrete with Recycled Concrete Aggregate in varying percentages of Natural Coarse Aggregate. A total of 20 concrete mixtures were prepared and tested, with different RCA content of 0, 25, 50, 75, and 100% at w/cm ratio of 0.38. About 50% of Portland cement in the mixtures were substituted by a combination of class C fly ash and granulated blast furnace slag. Base on the findings from the experiments, the following conclusions were outlined:

- Fly ash and slag increase the workability of SCC concrete for all mixtures with RCA.

- The results indicate that replacing the coarse aggregate with high percentages of RCA reduces the workability of the SCC.
- The addition of 25% FA + 25% SL in place of Portland cement increases the magnitudes of the slump flow.
- The usage of 50% FA in place of cement increased the slump flow in the mixtures with 75, and 100% RCA replacement, whereas the slump flow values were almost identical for the remaining design mixes with 0, 25, and 50% RCA replacement. This is presumably because of high utilisation of HRWRA on account of high-water absorption due to high RCA content.
- The addition of 50% SL to replaced Portland cement did not have any significant change on the slump flow.
- The lowest slump flow value was monitored when the coarse aggregate was replaced with 75% RCA and the cement by combination 25% FA + 25% SL, where the flowability of concrete very nearly achieves segregation.
- The compressive strength of the SCC decreases as the percentage of RCA increases. The addition of FA and SL to concrete has resulted in the reduction of the compressive strength at 3, 14 and 28 days. However, the decrease in the compressive strength of the mixtures containing FA was more significant than those containing SL or FA and SL.
- The 28-day compressive strength for Mixes C_{0FA50}, C_{0SL50}, and $C_{0FA25SL25}$ was less than that of C_0 (control mix) by 18.32%, 5.3%, and 15.6%, respectively. The inclusion of slag to mixtures had the minimal effect on the 3, 14, and 28-days compressive strength.
- As the RCA content increased from 0 to 100% the split tensile strength of all mixtures decreased accordingly. The maximum tensile strength recorded was 6.2 MPa which corresponds to the control mixture C_0 of 100% cement and 0% RCA, while the minimum recorded was 1.8 MPa, which corresponds to $C_{100FA50}$ of 50% fly ash and 100% RCA.
- Replacing the cement with 50% slag increased the tensile strength for all different RCA contents compared to replacing it with 50% fly ash and 25% fly ash and 25% slag.

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