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Research Article

Towards Sustainable Self-Compacting Concrete: Effect of Recycled Slag Coarse Aggregate on the Fresh Properties of SCC

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Steel industry results in accumulation of steel slag wastes causing severe environmental problems. These wastes can be recycled and replace natural aggregates resulting in sustainable green concrete. In this research, natural aggregates in self-compacting concrete (SCC) are replaced, wholly or partly, by steel slag coarse aggregates that were produced by crushing by-product boulders obtained from the steel industry. Fresh properties, (workability, stability, bleeding, air content, and fresh density) are the crucial ones that affect the final properties of SCC. Therefore, it becomes important to evaluate the impact of SSA on the fresh properties of SCC mixes. The properties that are studied include stability, flowability, blocking, segregation, and bleeding. Furthermore, air content and fresh density are measured. In order to evaluate the impact of SSA on SCC properties, several testing methods are employed. Slump flow, V-funnel, column segregation, sieve segregation, segregation probe, U-shaped box, and VSI tests have been used in the study. The results show that it is possible to produce SCC using steel slag aggregate. Hence, green sustainable SCC can be produced. The results show that the fresh properties become sensitive for SSA replacement ratios exceeding 50%.

1. Introduction

1.1. Importance of the Research. Waste materials from the steel industry are produced in high amounts and shapes ranging from large boulders to dust. Large quantities of these wastes are generated and are problematic and hazardous for both the factories and the environment.

Local steel industry is not based on using “steel ore” as a base material. Instead, scrap steel is brought from various sources, melted and shaped. In other words, pure steel and not iron oxides is used in the industry. The by-product is then air-cooled and stocked outside the steel mill. As a result, the waste material is characterized, relatively, by its high content of iron oxides, Fe_2O_3. The slag produced is divided into three types: coarse boulders, fine mill scale, and dust. The most problematic are the coarse boulders which accumulate by time. These boulders can be crushed into smaller sizes and then can be effectively used in concrete mixes [1–3].

Since the new trends in concrete construction goes towards self-compacting green concrete, it becomes important to study the possibility and effectiveness of using steel slag aggregate (SSA) in self-compacting concrete (SCC) as a replacement of coarse aggregate. SSA has higher density and higher angularity than normal aggregate [1]. These two properties have a direct effect on the fresh properties of SCC. Since stability is the crucial property for SCC, it becomes necessary to assess the stability of SCC when SSA is introduced.

The final properties of SCC, such as strength, durability, and serviceability, depend mainly on the properties and the quality of the materials that have been used. This will be the next aim of the research.

The use of waste materials, such as steel slag, in concrete may have positive or negative effects. Utilizing steel slag for concrete construction has proved to be useful in solving some of the problems encountered in the concrete industry. Steel slag has been used in conventional concrete to improve the mechanical, physical, and chemical properties of concrete, as shown herein. Furthermore, the use of slag in concrete as coarse aggregate would minimize the accumulation of slag wastes and reduce the environmental problems.

The research investigates the possibility of using SSA in SCC. The use of SSA as coarse aggregate in concrete proved to be beneficial [1, 2]. Since the new trends in concrete construction goes towards high performance self-compacting green concrete, it becomes important to study the behavior of concrete containing SSA as coarse aggregate. As workability and stability are the crucial properties that control the hardened properties of SCC, it becomes necessary to assess the stability of SCC when SSA is introduced. Because it is difficult to assess the stability by a single test, various tests have to be performed in order to assess the stability before any justification.

1.2. Use of Steel Slag in Normal and Self-Compacting Concrete. Slag, the by-product of steel and iron producing processes, was used in civil engineering tenths of years ago [4–7]. Portland granulated ground blast furnace slag cement, which is produced from rapidly water-cooled blast furnace slag, has been successfully used in concrete mixes due to its pozzolanic activity.

Although many studies have been conducted on the evaluation of steel slag usage, as coarse aggregate in road construction [8] and use of blast furnace slag in concrete mixes, fewer studies have been performed regarding the utilization of steel slag, as coarse aggregate, in normal concrete. Better mechanical properties are reported [7, 9–12]. Effect on durability is reported by Manso et al. [13, 14], Ramachandran [15], Pellegrino and Gaddo [16], Dippenaar [17], Hiltunen [18], Murphy et al. [19], and Faleschini et al. [20]. A positive effect on the hardened properties has been reported when local materials are used [1, 2].

While there is some research regarding the use of steel slag aggregate as a supplementary cementitious material in SCC, there is only very limited research regarding the use of coarse SSA in SCC. With regard to the use of steel slag as a fine material in SCC, the research showed that it is possible to produce SCC with better properties. Examples are herein. Boukendakdji et al. [21] showed that the use of Algerian steel slag as supplementary cementitious material in SCC is possible and that the stability of the mix could be attained. Peng and Hwang [22] used carbon steel slag (CSS) as a fine supplementary cementitious material in SCC. Sheen et al. [23] used steel reducing slags (SRS) as fillers and cement substitutions. Pole and Suresh [24] and Ali and Kakde [25] used GGBFS in SCC and improved SCC properties.

Regarding the use of SSA as coarse aggregate in SCC, very limited research could be found on the World Wide Web. Tomasiello et al. 2010 showed that it is possible to use SSA in SCC by replacing 30% of the natural aggregate by SSA. Yoo [26] studied the use of atomized steel slag aggregate in SCC. He concluded that SCC with and without atomized steel slag aggregate are all much the same in the fresh and hardened properties. The Indian experience is summarized in [26–28]. The last three papers concentrated on the effect of SSA on the hardened properties rather than the critical fresh properties. Santamaría et al. [29] showed that it is possible to produce SCC using SSA. They proposed criteria and methods for successful preparation of these mixtures. They proposed a method that estimates the viscous properties of the mixes and their workability, based on the dosage and the characteristics of their components.

2. Workability of SCC

In its fresh state, SCC should have four main properties in order to achieve the late hardened properties. These are summarized as follows:

- *Mobility*: the ability of SCC to flow freely under its own weight without any external help
- *Filling ability*: the ability of SCC to fill freely all parts and corners of the formwork (horizontally and vertically upwards) without segregation, separation, or bleeding
- *Passing ability*: the ability of concrete to flow easily through dense reinforcement and coat effectively all steel bars
- *Segregation resistance*: the ability of concrete to remain cohesive, coherent, and homogeneous during and after placement without segregation, separation, or bleeding

In addition to the previous properties, SCC must have bleeding resistance during all stages of production. Also it must have the suitable viscosity.

In order to measure the properties of fresh SCC concrete, several methods have been introduced and widely used. These tests try to measure or predict one or more of the four properties indicated above. Table 1 summarizes the common tests and their uses in the measurement of the previous properties. A comprehensive discussion of properties and tests can be found in Daczko [30] and EFNARC [31]. Furthermore, SCC can be assessed using rheometer. By the use of these tests, the viscosity and shear strength of concrete can be obtained and compared with other tests [29]. Some of these tests are included in Table 1.

3. Materials

Normal limestone aggregates from local sources were used in the study. The gradation was obtained using ASTM C136 and BS 882. Normal coarse aggregate was obtained by combining various aggregates of different single-sized aggregates in order to arrive at a grading accepted by ASTM and BS standards. Steel slag boulders were first crushed and screened in order to obtain the required sizes, as shown in Figure 1. Later, these materials were sieved in the lab using the standard sieves. The sizes were combined in order to obtain a gradation similar to that of the natural aggregates. Hence, the possible effects of the change of gradation on the properties of concrete are eliminated. Both the natural and the slag aggregates are within ASTM C33 and BS 882 grading requirements for coarse aggregate.

Natural sand, *known locally as desert sand and is the most commonly type used in local sites*, is used in all mixes. Gradation of the aggregate was obtained using ASTM C33

Table 1: Suitable tests for the various properties of SCC.

Property	Test
Mobility	Slump flow; $T_{50\,\text{cm}}$-slump flow; L-box
Filling ability	Slump flow; $T_{50\,\text{cm}}$-slump flow; U-box
Passing ability	L-box; J-ring; V-funnel
Segregation resistance	VSI; column segregation test
Bleeding	Bleeding test
Viscosity and shear strength	Two-point test; the IBB rheometer; the ICAR rheometer; the BML rheometer; BTRHEOM apparatus

and BS 882. The fineness modulus of sand is 1.46. The sand is classified as fine and is not within the ASTM C33-92 grading requirements. However, the sand is within the limits of BS 882:1992 standards and is classified as "F" (fine sand). Although this sand is relatively fine, it has good properties and is commonly used in concrete mixes.

The specific gravity and absorption of the aggregates were measured using ASTM C127-88 and ASTM C128-88. In each case, three representative samples were taken and tested according to the corresponding ASTM standard. The average of the three values was calculated and reported. The hardness of the aggregates was obtained using the Los Angeles (LA) abrasion test (ASTM C131-89). The angularity number was obtained using BS EN 12620:2013. The angularity of aggregate that is considered suitable for concrete is between 0 and 11 [5]. It is noted that the angularity number of SSA is close to 11, the max value. This relatively high angularity is responsible for possible loss of stability.

All the results are summarized in Table 2. The results show that the steel slag aggregates possess better properties than the natural aggregates. However, the density can be disadvantageous or advantageous depending on the design requirements. For example, it is advantageous if better stability against horizontal forces is required while it is disadvantageous if lighter structures are required.

Chemical analysis of steel slag was performed using XRF. The results are shown in Table 3.

The cement used in all mixes is ordinary Portland cement conforming to ASTM C150-92 specifications and is classified as Type I.

The HRWR is Hyperplast PC 260 admixtures which is a polycarboxylate (particularly polycarboxylated-ether copolymer (PCE)). The PCE admixtures are particularly effective as they give very fluid but cohesive concrete with good retention of high flow. The admixture is classified as G according to ASTM C 494. A viscosity modifying agent (VMA) was also introduced in small amounts to control the viscosity of some of the mixes, as will be discussed later. The same type and amounts have been used in all mixes for the sake of comparisons. Therefore, the effect of admixtures on the properties of the mixes is eliminated. The mix proportions are summarized in Table 4.

4. Experimental Program

In order to study the efficiency of the use of steel slag as coarse aggregates in SCC, several concrete mixes have been prepared and tested in the laboratory. The following steps summarize the program that has been followed:

Figure 1: Crushing and screening of slag boulders.

(1) Various SCC mixes have been prepared and tested in the lab. First, SCC reference mix has been designed and tested. Later, natural coarse aggregate has been partly or totally replaced by SSA. The SSA to natural aggregate ratios were 0, 25%, 50%, 75%, and 100%.

(2) Fresh concrete mixes have been tested in order to assess the workability properties that are described in Section 2. Several tests have been adopted: slump flow, sieve segregation test, segregation probe, column segregation test, V-funnel, and the L-shaped box.

(3) Visual stability analysis (VSI) was recorded when samples were tested in the slump cone.

(4) The bleeding of the mixes was measured.

(5) The air content and fresh density were also measured.

(6) The tests were repeated for three different *w/c* ratios.

5. Results and Discussions

5.1. Slump Flow. The test was performed according to ASTM C1611. The test gives a good indication about the mobility and

Table 2: Physical and mechanical properties of graded aggregate.

Property	Coarse aggregate	Fine aggregate	Steel slag aggregate
Specific gravity (SSD)	2.62	2.57	3.19
Water absorption (%)	1.67	0.9	0.8
Angularity number	6.3	—	10.4
LA abrasion (%)	23	—	17

Table 3: Chemical composition of slag (%).

Oxides	Fe_2O_3	FeO	MnO	SiO_2	MgO	CaO	P_2O_3	SO_3	Al_2O_3	Alkalis	Metallic iron
Slag in the research	37.0	—	2.9	15.5	6.6	29.7	0.4	0.3	4.7	0.9	—
Slag from steel ore	2–12	7–30	5–8	10–20	5–10	40–50	0.5–1	<0.1	1–3	—	0.5–10

Table 4: Mix proportions of normal concrete mixes.

	Normal mixes, values in kg/m^3							
Mixes	Water	Cement (OPC)	Sand < 5 mm	Coarse aggregate 5 to 12 mm	Microsilica (10% of cement)	Admixture (litre)	Water/binder ratio*	28-day compressive cube strength
Mix 1	185	440	990	710	44	11	0.40	51.5
Mix 2	180	460	965	735	46	11.5	0.38	53.6
Mix 3	170	490	935	755	49	12.25	0.34	58.4

*The water in the admixture has been included.

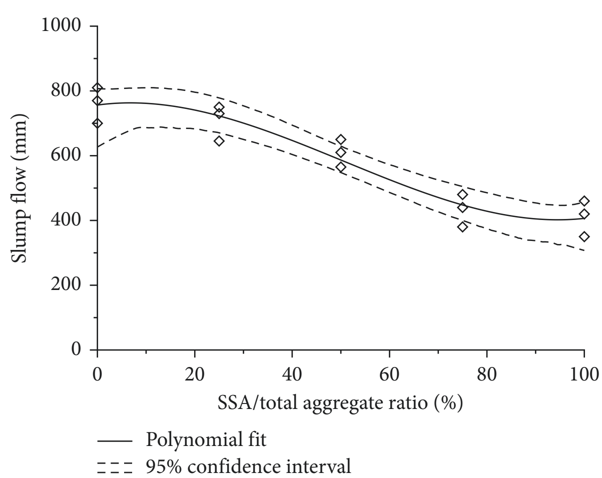

Figure 2: Relationship between the SSA replacement ratio and the slump flow.

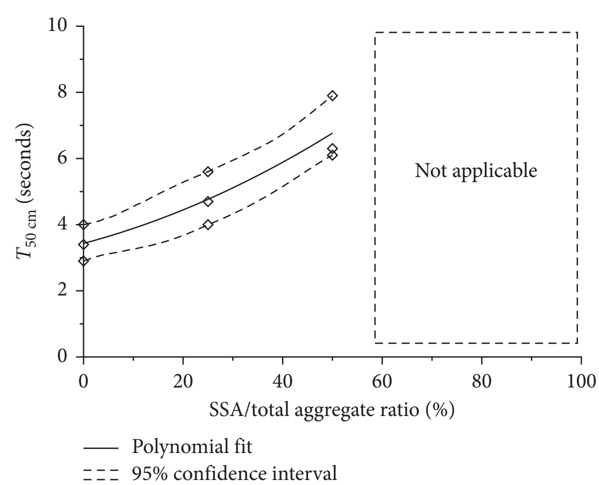

Figure 3: Relationship between the SSA replacement ratio and $T_{50\,cm}$ in the slump flow test.

flowability of SCC. It is widely used because of its simplicity and availability at sites. Two values are measured from the test:

(a) T_{50}, which is the time taken for the concrete to flow a distance of 500 mm

(b) The spread of concrete in mm

The results of the test for all replacements are shown in Figures 2 and 3. The addition of SSA reduced the slump flow. Increasing the replacement ratio more than 50% produced concrete of unacceptable flow. It is clear from the plot that the 500 mm value can be obtained when the SSA ratio is less than 50%. This could be attributed to the higher angularity of SSA which reduces the workability. As seen in Figure 3, T_{50} could not be obtained for the mixes containing more than 50% SSA. This leads to the conclusion that stable acceptable SCC cannot be obtained with high SSA replacement ratio. Results are consistent with Santamaría et al. [29]. They reported reduction in mobility of the mixes when SSA is introduced.

5.2. Visual Stability Index (VSI). In addition to the results in Section 5.1, the concrete, after flow, was visually inspected to obtain the visual stability index (VSI). The VSI is a visual evaluation of the static segregation of the SCC. It is measured according to ASTM C1712 and is rated to the approximate 0.5 increments by visual examination as specified in Table 5.

Table 5: VSI of the various mixes.

Ratio (%)		0	25	50	75	100
VSI	Operator 1	0.33	1.	1.5	1.83	2.5
	Operator 2	0.17	0.67	1.17	2.00	2.33
	Average	0.25	0.84	1.34	1.92	2.41
	Rating according to ASTM	HS to S	HS to S	S to U	S to U	U to HU

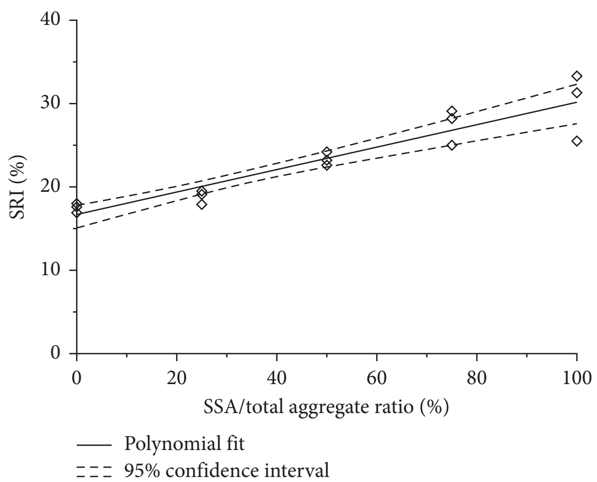

Figure 4: Relationship between the SSA replacement ratio and the SRI.

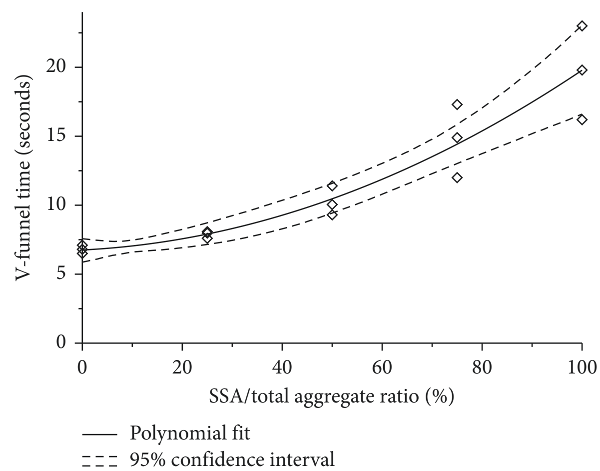

Figure 5: Relationship between the SSA replacement ratio and the V-funnel time.

Human errors may be encountered when assessing the VSI. Therefore, two experienced operators were allowed to assess the segregation and report the value to the nearest 0.5. Each value is the average of three VSI measurements. The results of the test for all replacements are shown in Table 5.

However, the visual stability index provides a quick but approximate indication of the stability of the mixture. On the other hand, an acceptable VSI does not always ensure adequate stability nor does an unacceptable VSI mean the concrete will be unstable [32]. Therefore, the use of other tests may be necessary to assess the stability of the mixes. This is what is done in this research.

5.3. Sieve Segregation Test. The sieve segregation test to BS EN 12350-11 is used to assess the resistance of SCC to segregation. The test gives a good idea about the possible segregation of SCC when placed in forms. The results are expressed as the segregation resistance index (SRI). The SRI is defined as the weight of concrete passing the 5 mm sieve over the total weight of concrete dropped onto the sieve. An acceptable segregation resistance index value is below 0.2 (20%) according to the European Guideline for SCC [31].

The results are shown in Figure 4. It is quite clear that the acceptable SRI is obtained only for mixes containing SSA ratio of less than 50%.

5.4. V-Funnel. The V-funnel is a test described in BS EN 12350-9:2010. It measures the flow time a defined volume of SCC needs to pass a standard narrow opening. The test is an indication of filing ability of SCC. The V-funnel time can be related to plastic viscosity [33].

The results are shown in Figure 5. Since the acceptance criteria is ≤15 seconds [31], mixes containing SSA ratio of 25% and 50% satisfy the criteria. In addition, two of the mixes containing SSA of 75% satisfied the criteria but none of the mixes containing 100% SSA did.

5.5. The Segregation Probe. The segregation probe is considered a simple, fast, and effective method to assess the segregation of concrete. The apparatus simply measures the thickness of mortar/paste at the top of fresh SCC by a specially shaped wire. The thicker the mortar/paste layer at the surface, the lower the static stability. Sonebi et al. (2007) found that the results of the segregation probe method and the measured thickness of the mortar/paste layer in hardened concrete were to be quite similar.

Table 6 shows the effect of SSA on the depth of the mortar/paste layer. All the results obtained in the test indicate that the use of slag has a marginal effect on the thickness of the mortar layer. The results show that the mixes are stable and that they correspond to a VSI of less than 2.

When compared to the stability rating measured by the VSI, as shown in Table 5, the results are different. The results here indicate that all mixes are stable, which is not truly the case. Based on that, it is recommended not to use this test in the evaluation of SCC containing SSA as coarse aggregates. For example, Figure 6 shows a sample with notable segregation in the solid state, but the probe measured value was only 5.5 mm.

5.6. L-Box. L-Box tests the flow rate, filling ability, and passing ability of SCC in between steel bars. It also measures

Table 6: The depth of the mortar layer as measured by the segregation probe.

Reference [34]		Thickness of layer (mm) for various ratios				
Penetration depth (mm)	Rating	0%	25%	50%	75%	100%
<4	0 stable	3.7	—	—	—	—
4~<7	1 stable	—	4.3	5	5.9	6.6
7–25	2 unstable	—	—	—	—	—
>25	3 unstable	—	—	—	—	—

Figure 6: A sample of notable segregation.

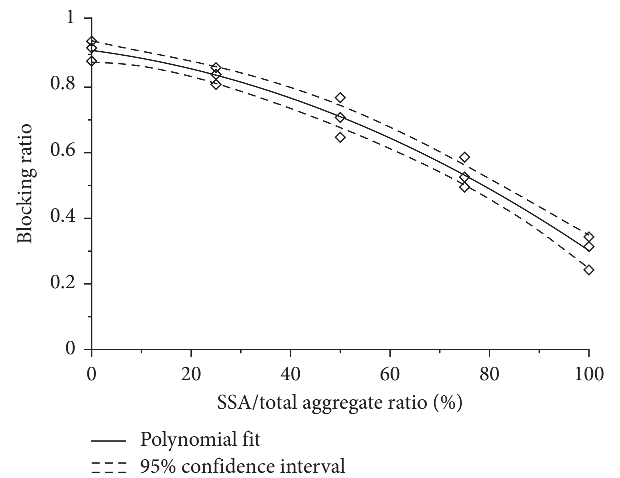

Figure 7: Relationship between the SSA replacement ratio and the blocking ratio.

the blocking ability of SCC, which is the ratio between the reached and the original heights of fresh SCC after passing through the specified gaps of steel bars.

The results of the test for all replacements are shown in Figure 7. The EU research team suggested a minimum acceptable value of 0.8, which is attained for replacement ratios not exceeding 25%.

5.7. The Settlement Column Segregation Test. The settlement column segregation test comprises a small column of SCC mix with internal dimensions of 500 mm × 150 mm × 100 mm. The concrete is jolted 20 times in one minute using the drop table and then allowed to stand for an additional five minutes to allow for settlement of concrete. The samples from the top and the bottom of the column are individually washed through a 5 mm sieve to leave only the coarse aggregate. The segregation ratio is then calculated as ratio of the mass of coarse aggregate in the top sample to the mass of coarse aggregate in the bottom sample. The lower this ratio is, the greater the susceptibility to segregation will be. This test is considered one of the best for evaluating the segregation of SCC (Sonebi et al. 2007).

The results are shown in Figure 8. The results are compared with the threshold limits suggested by Sonebi et al. (Table 7). The SCC is considered category 1 or 2 for replacement ratios of 25% and 50%. The other two are classified as category 3 indicating notable segregation. None of the tested mixes was in category 4.

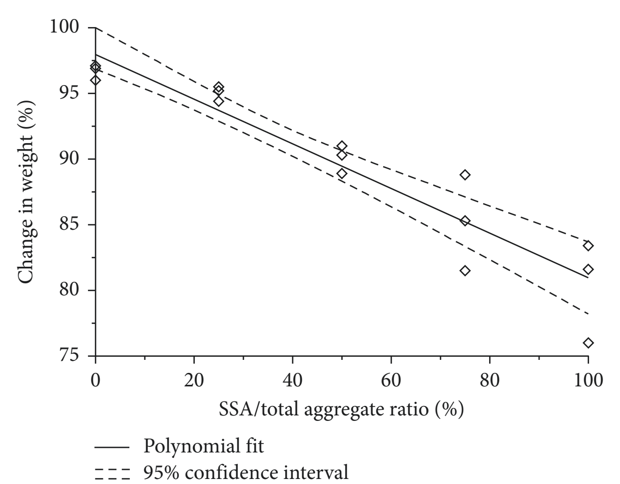

Figure 8: Relationship between the SSA replacement ratio and the change in weight in the column segregation test.

5.8. The Bleeding Test. The bleeding was measured using a test similar to the one described by ASTM C232. Concrete was placed in a steel mould. The mould was then placed at a small angle, covered and left to stand for the duration of the test. A syringe was used to draw off the bleed water and collect it in a special tight flask. At the end of the test, the collected water was weighed using an electronic balance. The bleed water was calculated and expressed as a percentage of the amount of mixing water in the sample. The results are plotted in Figure 9. It is noted that the bleed water increases sharply when the replacement ratio exceeds 50%. It is quite clear that the bleed water exceeds the limit of 2.5% at about 40% replacement ratio. According to Ben aicha et al. [35], the rheological properties of self-compacting concrete mixtures are closely related to their bleeding index.

Table 7: Segregation threshold (Sonebi et al.) and classification of the tested concrete.

		Category for each SSA replacement ratio (average value)	
Settlement category	Settlement ratio (%)	0%	Values between 96 and 97 (Cat. 1)
(1) No segregation	>95	25%	Values between 94 and 96 (Cat. 1 and 2)
(2) Mild segregation	88–95	50%	Values between 88 and 91 (Cat. 2)
(3) Notable segregation	72–87	75%	Values between 81 and 89 (Cat 3)
(4) Severe segregation	<71	100%	Values between 76 and 83 (Cat 4)

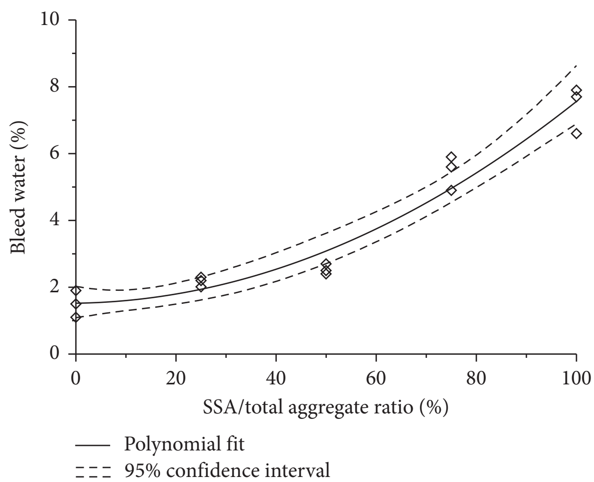

Figure 9: Relationship between the SSA replacement ratio and amount of bleed water.

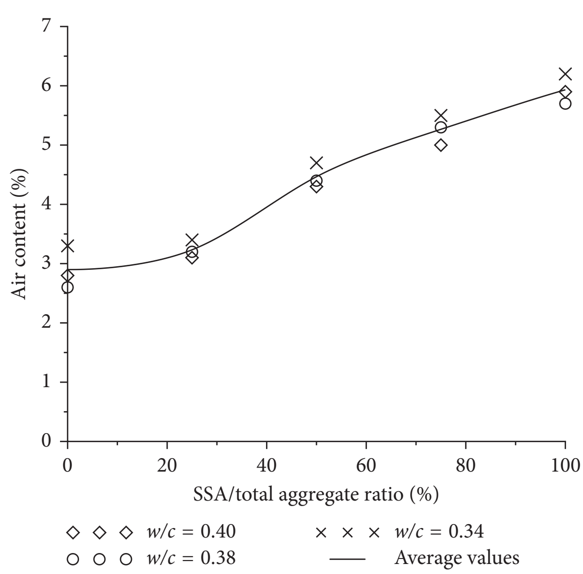

Figure 10: Relationship between the SSA replacement ratio and air content.

5.9. Air Content. Air content of concrete was measured using the method described in ASTM C231. The results are shown in Figure 10. From the figure, the use of SSA resulted in a slight increase in the air content for replacements less than 50%. Air content was approximately doubled when all virgin aggregates were replaced by SSA. The increase in air content may be attributed to the higher angularity of SSA, which could capture more air voids in their packing voids. Furthermore, some of the mixes containing 75% and 100% SSA were not good enough to be self compacted, which may result in increase in air content.

The study is supported by Kostrzanowska-Siedlarz and Gołaszewski [36]. They showed that the air content of fresh high performance SCC depends on the universal components of the mix.

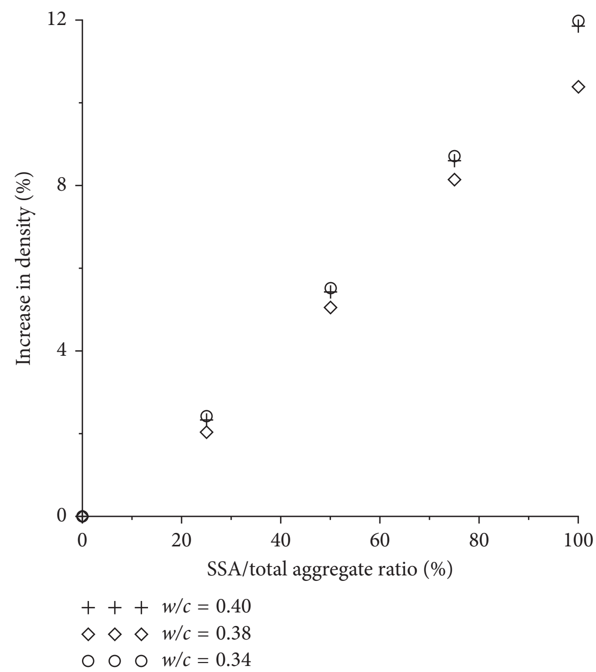

Figure 11: Relationship between the SSA replacement ratio and increase in density (%).

5.10. Fresh Density. Figure 11 shows the change in the density of concrete. As expected, the density of concrete increases by the increase in SSA replacement ratio. The increase in density can be attributed to higher specific gravity of SSA and the better interaction between angular aggregates. Higher densities are reported for concrete containing SSA [1, 29].

In order to make better comparison between results, the air-free density was calculated using the relationship: $\text{air}-\text{free density} = \text{fresh density}/(1-\text{air content})$. The results are plotted in Figure 12.

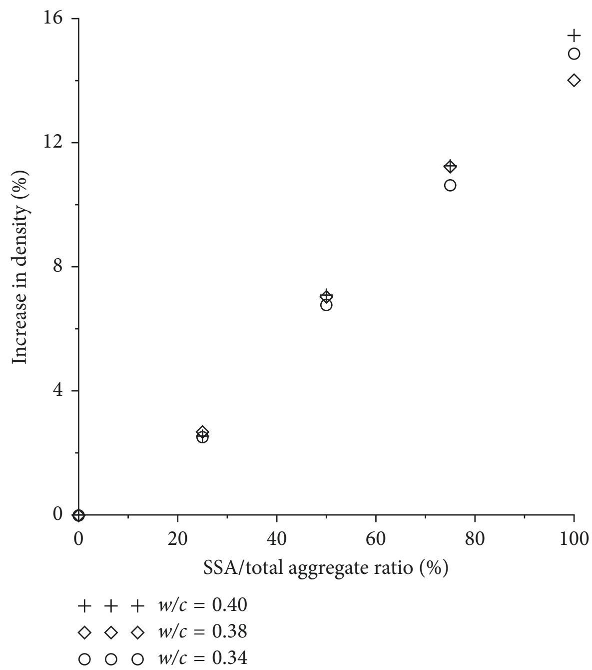

Figure 12: Relationship between the SSA replacement ratio and increase in the air-free density (%).

From the figure, it can be seen that increasing the SSA replacement value results in increase in the air-free density. Higher replacements showed higher increase in the air-density because of the high specific gravity of SSA and the high air content in fresh mixes.

6. Conclusions

Based on the research, concerning the use of steel slag as coarse aggregate in SCC and presented in this paper, the following are observed:

(1) The use of steel slag in SCC, as coarse aggregate, is possible and thus beneficial for the environment where the slag can be dumped in concrete rather than the soil. Hence, green SCC can be produced.

(2) SCC can be produced using SSA as coarse aggregate without losing its stability, which is the crucial property for SCC production.

(3) The use of steel slag has an adverse effect on the workability and stability of SCC. This effect increases by the increase of SSA in the mixes.

(4) Under the same conditions, up to 50% of the normal coarse aggregate can be replaced by SSA without adverse effects on the stability or flowability of SCC. In other words, most of the criteria required for SCC are still valid.

(5) Higher replacement ratios (above 50%) can also be used but may require more cement, microsilica, and admixtures. Such use would result in increase in the costs of the mixes.

(6) Although it is acceptable to use the segregation probe to evaluate the stability of normal SCC, it may not be suitable for testing concrete containing SSA.

(7) In practical applications, it is important to assure flowability and segregation resistance of SCC containing SSA. In this respect, the slump flow may be quite suitable for flow of concrete because of its simplicity and extensive use. For segregation, the column segregation test, together with the VSI from slump flow can be quite suitable. I suggest these two tests for the site.

(8) The use of SSA in concrete increases air content in fresh mixes. However, this increase is small for SSA ratios not exceeding 50%.

(9) The use of SSA in concrete increases its fresh density. However, this increase is small for SSA ratios not exceeding 50%.

(10) Air-free density is increased, especially in mixes containing high amounts of SSA.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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