Destructive and Non-Destructive Test Characteristics of Concrete Produced with Iron Slag Aggregate

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ABSTRACT
The ground granulated Blast furnace slag (GGBFS) is a waste of industrial materials; it is relatively more recent pozzolanic material that has received considerable attention in both research and application. In the present investigation, Blast Furnace Slag from local industries has been utilized to find its suitability as a coarse aggregate in self-compactible concrete (SCC) making. Replacing all or some portion of natural aggregates with slag would lead to considerable environmental benefits. SCC mixes were designed and coarse aggregates were replaced by 0, 20, 40, 60, 80, and 100% steel slag by weight. Tests were conducted to assess the fresh properties, strength properties, and durability behavior (permeability) of SCC. Properties such as slump flow, flow diameter, passing ability, segregation resistance, compressive strength, and both rebound number and ultrasonic pulse velocity were measured. In addition, the relationship between compressive strength and rebound number as well as the ultrasonic pulse velocity (UPV) was discussed. Splitting tensile strength, flexural strength, and permeability were also examined. The results indicate that the mixture of 60% replacement (SCC-SA60) was selected as the optimum mixture in which compressive strength, splitting tensile strength, and flexural strength increased by 5%, 35%, and 10%, respectively. Permeability increased with increasing the steel slag content. The results also illustrated that there is a significant relationship between compressive strength and UPV as well as rebound number for the SCC mixes.

KEYWORDS
Steel slag; mechanical properties; permeability; UPV; rebound number

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Many researches on slag aggregate concrete mixes have shown that the mechanical strengths and durability aspects are more influenced by design parameters such as the cement content, concentration of soluble and water/binder ratio (Cheng & Chiu, 2003) and (Al-Otaibi, 2008). The strength development in slag aggregate concrete mixes is additionally subordinate on chemical composition, particle size distribution, accessible crystalline stages and glass substance within the raw slag being utilized in their generation (Bernal, De Gutiérrez, & Provis, 2012) and (Qureshi & Ghosh, 2014).

The resistance of the slag aggregate concrete comes from the lower porosity compared with the conventional concrete. It can be concluded that the compressive strength depends on the nature and strength of the formed hydrates, on their association mode and on the porosity (Senani, Ferhoune, Guettala, & Aguiar, 2018). Replaced aggregate concrete (PAC) has lower penetrability than conventional concrete that improves the durability of concrete. Inclusion of slag aggregate improves the resistance to chloride ion penetration in both PAC and conventional concrete. Shrinkage produced by PAC is significantly lower than that of conventional concrete (Kunal, Das, Lam, & Tang, 2020) and (Gaurav, Souvik, Abdulaziz, & Saha, 2015).

The objective of this study is to experimentally examine the impact of using SA on mechanical and durability characteristics of SCC. The accumulation of these materials is considered as a serious danger to the environment and therefore, recycling them is a must to save our world. The influence of type and amount of aggregate is very important and cannot be neglected for accurate prediction of compressive strength of concrete based on rebound number and ultrasonic pulse velocity.

**Experimental work**

SCC mixes in this research are combined type (produced using viscosity modifying admixture and fine materials). FA was used as fine materials. It was used as a partial replacement of cement in order to enhance fresh properties and durability of SCC. Slag aggregate (SA) was used as a partial replacement of dolomite.

### Table 1. Chemical Analysis of (OPC, and Fly Ash, Dolomite, and Slag aggregate).

| %Compound | CEM I 42.5 N | Fly Ash | Dolomite | Slag Aggregate |
|-----------|--------------|---------|----------|---------------|
| SiO₂      | 20           | 36.41   | -        | 27.54         |
| Al₂O₃     | 11.68        | 15.43   | 1.09     | 4.91          |
| Fe₂O₃     | 2.5          | 0.69    | 0.22     | 61.22         |
| CaO       | 56           | 34.12   | 74.26    | 2.80          |
| MgO       | 3.4          | 10.26   | 21.42    | 1.60          |
| SO₃       | 2.2          | -       | 0.85     | 0.53          |
| K₂O       | 0.91         | 0.97    | 0.38     | 0.75          |
| Na₂O      | 0.35         | 0.35    | 1.26     | 0.65          |
| Cl         | 0.07         | 0.12    | -        | -             |
| Loss on Ignition (LOI) | 2.89 | 1.65 | 0.52 | - |

### Characteristics of different materials

The utilized cement was OPC (Ordinary Portland Cement (CEM I 42.5 N) with specific gravity 3.15. Type F fly ash (FA) was utilized as fine materials. It was utilized as a partial replacement of cement. Slag aggregate (SA) was used as a partial replacement of dolomite. Dolomite and slag aggregate were used as coarse aggregate. The water absorption of slag aggregate and dolomite are 0.50 and 1.15, respectively. Table 1 shows the chemical analysis of OPC, FA, D and SA. The fine aggregate utilized was characteristic siliceous sand with fineness modulus of 2.34. Viscocrete admixture was used as a superplasticizer and powerful water reducer. The used materials are described as follows.

- **Cement**: Portland cement CEM 42.5 N produced by Arabian Cement Company complying with the Egyptian standard specifications ES4756-1/2009 and EN 197–1/2000.
- **Coarse aggregate**: Dolomite from EMACOM with nominal maximum size of 4.75–19 mm, specific weight 2.65, volumetric weight 1.59 kg/m3.
- **Slag aggregate**: from iron industries with nominal maximum size of 4.75–19 mm, specific weight 3.80, volumetric weight 2.28 kg/m3.
- **Fine aggregate**: clean sand with fineness modulus of 2.3 and specific gravity 2.64.

Fly ash: Class F fly ash is used as finely divided powder of light gray color, with less than 10% retained on 45 μm sieve, bulk weight 0.9 t/m2, specific density 2.3.

Super plasticizer (SP): Viscocrete-3425 produced by Sika with density 1.05 kg/Lt.

### Table 2. Mixture proportions.

| Specimen code | water/amu | Cement | Fly Ash | Sand | Dolomite | Slag Aggregate | Viscocrete |
|---------------|-----------|--------|---------|------|----------|---------------|-----------|
| SCC- SA0      | 140       | 320    | 80      | 944  | 944      | 0             | 2.80      |
| SCC- SA20     | 140       | 320    | 80      | 944  | 189      | 755           | 2.80      |
| SCC- SA40     | 140       | 320    | 80      | 944  | 378      | 566           | 2.80      |
| SCC- SA60     | 140       | 320    | 80      | 944  | 566      | 378           | 2.80      |
| SCC- SA80     | 140       | 320    | 80      | 944  | 755      | 189           | 2.80      |
| SCC- SA100    | 140       | 320    | 80      | 944  | 0        | 944           | 2.80      |
Mix proportion

Six mixes were performed with 0.35 w/b ratio and 1.0 S/A ratio as shown in Table 2. The control mix SCC-SA0 was prepared without using any slag aggregate. FA was used as 20% partial replacement of cement. SA was used as 20%, 40%, 60%, 80%, and 100% partial replacement by weight of dolomite, for mixes SCC-SA20, SCC-SA40, SCC-SA60, SCC-SA80, and SCC-SA100, respectively.

Testing procedure, Set-up and Instrumentation

The materials were mixed using rotating drum mixer. The content of sand, cement, FA, dolomite, and/or slag aggregate was dry mixed all together in the mixer for 1 minute. Then, adding water and the mixing continued for further 2 minute. Viscocrete was then added and the mixing process continued for further 2 minute for full homogeneity before casting in molds. Once the time of mixing completed, the slump flow test, L-box test, and Sieve stability segregation test were carried out in rapid sequence, Figure 1. These tests were performed according to (EFNARC, 2005). The slump flow diameter values were determined as the average of two measured diameter of flowed concrete. The L-box height ratio by means of H2/H1 ratio was determined to specify the passing ability of the SCC. The segregation resistance was determined according to sieve with 5 mm square apertures. The fresh concrete is allowed to stand for 15 min. The top part of the sample is then poured into the sieve. After 2 min the weight of material that passed through the sieve is recorded. The segregation ratio is then calculated as the proportion of the sample passing through the sieve. SCC was placed into molds under its own weight without compaction. The samples were left for 24 hours in molds. Compressive strength test was carried out on cubes (150x150x150 mm) according to (ECP, 2020). Splitting test was carried out on cylinders (150x300 mm) according to (ASTM C496, 2002). Flexural strength test was carried out on prisms (100x100x500 mm) according to (ASTM C496, 2002). Water permeability test was carried out according to (ASTM C432-04, 2002) appliance at four cells. This fully automatic appliance is designed to carry out water permeability tests on cylinder specimens 150 mm diameter, as shown in Figure 2. The water penetration depth measured is taken as the average value of the greatest penetration depths on three test specimens. The permeability coefficient is measured by using the following equation:

\[ K = \frac{x^2}{2ht} \]  

where

- \( K \) = coefficient of permeability (cm/sec)
- \( X \) = average value of the greatest penetration depths on three test specimens (cm)
- \( h \) = applied pressure on the test specimens (30 kg/cm² i.e \( h = 30\times1020 = 3060 \text{ cm of water} \))
- \( t \) = duration of pressure application (sec)

Nondestructive tests (ultrasonic pulse velocity (UPV) test and rebound hammer test) were carried out on cubes (150x150x150 mm) at ages 7, and 28 days, Figure 3. The ultra-sonic pulse velocities of the concrete cubes were measured according to (ASTMC597-02, 2002) using transducers with

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**Figure 1.** Fresh concrete tests: slump flow, L-Box and segregation resistance test.

**Figure 2.** Water permeability test.
frequency (51) kHz, as shown in Figure (3a). Two readings on each cube were measured (using the lateral surfaces of the cube).

The rebound number was measured by Schmidt hammer and according to (ASTMC805-02, 2002). Each cube was fixed by applying (8) MPa using a compression machine to avoid any movement during this test as shown in Figure (3b). Five readings were taken on two opposite surfaces of the cube.

**Results and discussions**

**Fresh properties of concrete**

The results of fresh concrete tests are given in Table 3. The acceptable range for SCC for slump is 600-800mm, for T50 is 3-5sec and for passing ability with L-box test 0.8-1.0. For segregation resistance with sieve stability test, the acceptable values are 5-15%. The obtained results indicate that all the prepared SCC mixes have fresh properties within the acceptable range for SCC, and that addition of slag aggregate improved the workability (filling ability), passing ability and segregation resistance of SCC. From visual inspection, it might be attributed to the fact that slag aggregate’s sharp angle is less than dolomite aggregate as well as it has relatively smooth surface which provides ease in flow. The results of the density of every fresh concrete mixture were shown in Table 3. The density of specimens ranged from 1830 to 2470 kg/m³. Regarding the fact that slag aggregate has a higher specific gravity than dolomite, increase in the substitution slag aggregate for dolomite in fresh concrete can increase fresh concrete’s density linearily; actually with the replacement of dolomite aggregate by 100 percent slag aggregate (SCC-SA100), the density of fresh concrete reached 2470 kg/m³ that is approximately close to conventional plain concrete (about 2400 kg/m³). Moreover, the replacement of dolomite aggregate by 100% slag aggregate increased the density of concrete 26% to control concrete.

**Compressive strength (Fc)**

The average compressive strength; fc, tensile strength, and the flexural strength at various ages for all the investigated six SCC mixes are recorded in Table 4. The development of the compressive strength with time can be monitored from Figure 4. It can be noticed that, there was continuous increment of the compressive strength with increasing SA replacement ratio until reaching 60%. However, the strength started to decrease past that point of substitution level. Indeed, in spite of the fact that the SCC with 80 and 100% SA

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**Table 3. Fresh Properties of Tested Mixtures.**

| Mix code | Flowability (mm) | H₁ | H₂ | Passing ability (H₂/H₁) | Segregation resistance | Density (kg/m³) |
|----------|------------------|----|----|-------------------------|------------------------|-----------------|
| SCC-SA0  | 650              | 8  | 6  | 0.75                    | 0.10                   | 1830            |
| SCC-SA20 | 680              | 9  | 6.90 | 0.77                   | 0.125                | 2050            |
| SCC-SA40 | 700              | 9  | 7.00 | 0.78                   | 0.13                  | 2175            |
| SCC-SA60 | 710              | 8.5| 7.10 | 0.83                   | 0.133                 | 2330            |
| SCC-SA80 | 720              | 9  | 7.55 | 0.84                   | 0.145                 | 2390            |
| SCC-SA100| 740              | 8.5| 7.6  | 0.89                   | 0.15                  | 2470            |

**Table 4. Mechanical Properties of Concrete (Compressive, indirect tensile and flexural strength (MPa)).**

| Mix        | Compressive strength | Indirect tensile strength | Flexural strength |
|------------|----------------------|---------------------------|-------------------|
|            | 7 days | 28 days | 56 days | 90 days | 7 days | 28 days | 7 days | 28 days |            |
| SCC-SA0    | 23.15  | 36.23  | 37.026  | 41.04   | 2.19   | 2.31    | 4.54   | 5.08    |            |
| SCC-SA20   | 23.78  | 36.86  | 39.11   | 42.22   | 2.30   | 2.43    | 4.88   | 5.14    |            |
| SCC-SA40   | 28.48  | 37.37  | 39.85   | 43.70   | 2.39   | 2.59    | 5.08   | 5.35    |            |
| SCC-SA60   | 29.05  | 38.20  | 40.15   | 45.10   | 2.56   | 3.13    | 5.24   | 5.62    |            |
| SCC-SA80   | 28.89  | 37.79  | 39.85   | 44.29   | 2.22   | 2.93    | 4.73   | 5.49    |            |
| SCC-SA100  | 25.55  | 37.26  | 38.66   | 44      | 2.04   | 2.61    | 4.63   | 5.33    |            |
(SCC-SA80 and SCC-SA100) had lower compressive strength than the mix SCC-SA60, they had higher strength values in comparison to the control one.

As it measured, the compressive strength of control concrete at 90 days was 41.04 MPa. The most noteworthy increment in compressive strength was 45.10 MPa. It can be visually noticed that the quantity of paste around the aggregates in dolomite concrete is small and mechanical and physical properties of utilized aggregates straightforwardly affect the mechanical properties of concrete such as compressive strength (Zhang, Zhang, Yan, & Liu, 2017) and (Ibrahim, Abdul Razak, & Abutaha, 2017). Moreover, there is a decrease of strength in mixes with more than 60% replacement of aggregate; it was 44.29 MPa and 44 MPa for 80% and 100% replacement respectively. Researchers portrayed that the ideal percent of steel slag shifted from 40% to 50% (Al-Jabri, Hisada, Al-Oraimi, & Al-Saidy, 2009), while others ensures 60% of substitution as the ideal percentage (Sharma and Khan, 2018) and (Daniel, Shelton, & Jebadurai, 2016).

Agreeing to scanning electron microscope (SEM) given by past investigations (Wu, Zhang, & Ma, 2010), concrete mixes with 80% and 100% replacement with steel slag aggregate caused an increase in pore structure of concrete; hence, these changes may be the reason for the diminishment in strength of mixes with more than 60% steel slag in this study.

**Indirect tensile strength**

The splitting strength for tested specimens is displayed in Table 4. The results varied from 2.31 MPa to 3.13 MPa. It can be concluded that utilizing slag aggregate led to an increase in the tensile strength similar to the compressive strength. Also, the most noteworthy increment in flexural strength was found in mixes with a 60% substitution of dolomite with steel slag aggregate. It can be seen that an increase of 16.89 and 35.49% in tensile strength is achieved for SCC-SA60 mix at 7 and 28 days, respectively, compared to control one, Figure 5.

**Flexural strength**

The results displayed that the flexural strength varied from 5.08 MPa to 5.62 MPa, Table 4 and Figure 6. It can be concluded that, replacing dolomite with steel slag lead to an increment in the flexural strength as it did in the indirect tensile and compressive strength. Moreover, the highest increment in flexural strength was found at 60% slag aggregate similar to the trend seen for splitting and compressive strength. The extraordinary sort of aggregate, higher hardness, and mechanical characteristics of steel slag improved the flexural strength of mixtures. It can be shown that

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![Figure 4. Compressive Strength of mixes at different ages.](image)

![Figure 5. Indirect tensile strength of mixes at different ages.](image)
a 15.70 and 10.60% increase in flexural strength was gained for SCC-SA60 mixes at 7 and 28 day, respectively, compared to the control one.

**Permeability**

The water permeability results are plotted in Figure 7. It is observed that the permeability of specimens varied from 3.36211E-10 cm/s to 2.0595E-09 cm/s. It can be concluded that, replacement of dolomite with 100% steel slag increased the water permeability. Permeability is dependent on the pore size shown within the concrete (Ibrahim & Abdul Razak, 2016). Therefore, water permeability increased with increasing the replacement percentage of dolomite with slag aggregates, and the highest permeability of 2.0595E-09 cm/s was obtained for SAC mixes. The pore structure is primarily dependent on aggregate shape, and size (Yeih, Fu, Chang, & Huang, 2015). Therefore, increasing the amount of steel slag aggregate in the mixture increased porosity. Also, slag aggregates are heavy in weight compared to dolomite, as a result, slag aggregates settle down and water rises to the surface causing the increment in voids, changing the microstructure to a permeable one (Daniel et al., 2016). The average penetration depths are 1.4, 2, 2.6, 2.9, 3 and 3.3 cm for mixes SCC-SA0, SCC- SA20, SCC- SA40, SCC- SA60, SCC- SA80, and SCC- SA100, respectively.

**Rebound number results**

The rebound number test results show the impact of slag coarse aggregate replacement on the rebound number of SCC. Moreover, the relationship between rebound number and compressive strength is explored at ages of 7 and 28 days. From Table 5, it can be concluded that, the rebound number increases as slag aggregate content increases. It is observed a relationship between compressive strength and rebound number for SCC regardless of the difference.
The Ultrasonic Aggregate $(\text{U})$ in 98 V days.

\[ F_{cu} = 1.269e0.841V(7\text{days}) \quad (4) \]

\[ F_{cu} = 0.888e0.880V(28\text{days}) \quad (5) \]

where $F_{cu}$: compressive strength of SCC using Dolomite-Iron Blast Furnace Slag mixed Aggregate (Mpa)

$V$: Ultrasonic plus velocity

The results in Table 6 and Figure 8 confirm the reliability of the proposed method for the estimation of the concrete compressive strength with different UPV.

### CONCLUSION

Blast furnace slag is a byproduct and using it as aggregates in concrete will might prove an economical and environmentally friendly solution in local region. The demand for aggregates is increasing rapidly and so as the demand of concrete. Thus, it is becoming more important to find suitable alternatives for aggregates in the future.

This research tried to find the effect of using steel slag aggregate. So, six mixes for replacing the dolomite coarse aggregate with steel slag aggregate varying from 0% to 100% were utilized in this study. Finally, the following results were obtained:

- In fresh concrete mixes, increase in the percentage of replacing the dolomite aggregate with steel slag aggregate increased the density of fresh concrete that was related to the higher

### Ultrasonic pulse velocity result

The ultrasonic pulse velocity test results are presented in Table 5 to display the impact of incorporating slag aggregate on the ultrasonic pulse velocity of SCC. Moreover, the relationship between ultrasonic pulse velocity and compressive strength is investigated. It can be noticed that the ultrasonic pulse velocity increases as slag aggregate content increases.

Equations (4) and (5) were proposed to predict the 7 and 28 days compressive strength from, respectively, UPV values for SCC produced with Iron Blast Furnace Slag Aggregate. Equations (4) and (5) were in a very good agreement with (Mohamed-Ali et al., 2016).

### Table 6. Measured and predicted compressive strength of SCC mixes at 7 and 28 days.

| Mix   | Measured compressive strength (MPa) | Predicted compressive strength using rebound number (MPa) | Predicted compressive strength using Ultrasonic plus velocity (MPa) |
|-------|-------------------------------------|-----------------------------------------------------------|---------------------------------------------------------------|
|       | 7 days                 | 28 days            | 7 days               | 28 days               | 7 days               | 28 days               |
| SCC-Sa0 | 23.15                  | 36.23              | 19.22                | 35.63                | 25.25                | 36.50               |
| SCC-Sa20 | 23.78                  | 36.86              | 23.72                | 36.32                | 28.87                | 37.00               |
| SCC-Sa40 | 28.48                  | 37.37              | 28.22                | 36.80                | 30.89                | 37.96               |
| SCC-Sa60 | 29.05                  | 38.20              | 32.08                | 39.79                | 36.29                | 41.06               |
| SCC-Sa80 | 28.89                  | 37.79              | 30.15                | 37.23                | 29.50                | 38.75               |
| SCC-Sa100 | 25.55                 | 37.26              | 25.65                | 36.80                | 27.56                | 38.05               |

Figure 8. Comparison between measured and predicted compressive strength of SCC mixes at 28 day
specific gravity of steel slag aggregate than the dolomite aggregate. The increase in the density of SCC-SA100 was 26%.

- Utilizing higher percentage of slag aggregate is advantageous in self-compacting concrete, due to the enhancement of the fresh properties. The increase in the slump flow, passing ability, and segregation resistance of SCC-SA100 was 14%, 19%, and 0.5%, respectively.

- The results of permeability test demonstrated that increase in the incorporation of steel slag led to an increase in the percentage of permeability. According to the narrow range of the increase in permeability, it was concluded that these phenomena were related to special and glass texture of steel slag aggregate compared to the dolomite aggregate.

- Different mechanical tests including compressive, flexural, and tensile strength tests were performed in this study, and the results revealed that using steel slag aggregate generally led to an increase in the concrete strength compared to dolomite aggregate. For example, 60% replacing of dolomite aggregate with steel slag aggregate caused a 5%, 35% and 10% increase in compressive, flexural, and tensile strength of mixes, respectively.

- According to the strength values, and permeability of tested specimens, the mixture of SCC-SA60 was selected as the optimum mixture regarding its compressive, tensile, and flexural performances.

- Replacing the dolomite aggregates in concrete applications with steel slag would lead to considerable environmental benefits and at the same time the strength properties of the concrete is increased and would be economical.

- The compressive strength values resulting from the best-fit equations with ultrasonic pulse speed and rebound number are in a good agreement with those from the experimental tests.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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