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# Use of local discarded materials in concrete

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**Abstract**

Steel slag, a by-product of steel manufacturing, is generated in large quantities in Qatar. In fact, it is estimated that more than 400,000 tons of steel slag are generated annually in the country. Gravel, resulting from washing sand, is also produced at more than 500,000 tons/year in Qatar. Both materials are not efficiently used in the country and most of its aggregate (gabbro) needs are imported from neighboring countries. This paper presents the results obtained on the use of steel slag, gravel and gabbro in concrete. A total of nine concrete mixtures were prepared. One concrete mixture that contained 100% gabbro aggregate was considered as the control mix. Four concrete blends containing 100%, 75%, 50%, and 25% steel slag (by weight) were prepared as partial replacements of gabbro aggregates. Another four concrete mixtures containing 100%, 75%, 50%, and 25% gravel (by weight) were cast as partial replacements of gabbro aggregates. All samples were cured in a water tank for 7, 28 and 90 days and then subjected to compressive, flexural and splitting tensile strength tests. All concrete mixtures prepared easily met the 28-day compressive strength design requirement of 28 MPa. Best results were obtained for concrete prepared using 100% steel slag aggregates. Concrete cast using 100% gravel yielded lower strength results than the control mixture (100% gabbro). However, there was an increase in strength values with an increase in gabbro content in gravel/gabbro mixtures. Additional work is necessary to establish long-term performance, especially concerning what is reported in the literature about the expansive characteristics of steel slag aggregates when used in concrete. It should be noted that concrete cured for 90 days in the water tank did not exhibit any reversal in strength.



*Keywords:* Slag; Gabbro; Concrete; Waste; Recycling

## 1. Introduction

Steel slag, a by-product of steel manufacturing, is generated in large quantities in Qatar. In fact, it is estimated that more than 400,000 tons of steel slag are generated annually in the country. Gravel, resulting from washing sand, is also produced at more than 500,000 tons/year in Qatar. Such materials are not efficiently utilized in Qatar. However, the country suffers from the availability of good aggregates that could be utilized in road, parking, buildings and other construction. Also, as a result of infrastructural renewal in Qatar there will be a great demand for aggregates and other construction materials over the next ten years. It is estimated that more than 15 million tons of aggregates are imported each year to Qatar from Oman, the United Arab Emirates and Saudi Arabia, thereby, increasing construction costs and probably causing unnecessary project delays. Thus, our environmental responsibilities and potential economic benefits that might be realized dictate that we utilize steel slag, gravel and other discarded materials in the construction sector.

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Many countries including the United States of America, Britain, Australia, India and others routinely use steel slag in road bases and subbases, asphalt concrete paving, and other applications. A wide spread use of steel slag is not prevalent in Qatar yet. Research was thus needed to promote and investigate, where possible, the recycling of steel slag and gravel deposits (generated as a result of sand washing) in concrete mixtures.

This paper will present the results obtained from a research project on the use of steel slag, gravel and gabbro (imported aggregates) in concrete.

## 2. Literature review

Several research studies (Maselehuddin and Khan, 1999; Maseluhddin et al., 2003; Bosela et al., 2008; Patel, 2008) were conducted on the use of steel slag aggregates in concrete. Control mixtures were prepared using natural aggregates such as limestone and crushed gravel. Trial concrete mixes were also cast using different percentages of steel slag aggregates as substitutes for coarse natural aggregates. Fresh and hardened concrete were subjected to mechanical and durability tests. All laboratory results indicate that concrete prepared using steel slag aggregates produced equal or better performance than that of concrete cast using coarse natural aggregates.

However, there were no serious attempts to investigate the performance of fresh steel slag aggregate against aged aggregates in concrete. Also, data regarding long-term concrete performance are limited and inconclusive, especially concerning the expansive characteristic of steel slag aggregate. Much research work remains to be done in this regard.

On another note, granulated blast furnace slag has been extensively studied for use in cement and concrete. This slag is accepted for use in the construction industry. Several research studies (Dongxue et al., 1997; Altun and Yilamz, 2002; Shi and Hu, 2003; Baby, 2012; Kounrounis et al., 2007) investigated also the use of steel slag in composite cements. Concerns were raised concerning the low content of reactive calcium silicate compounds and the potential for expansion due to the high content of free calcium and magnesium oxides.

Kounrounis et al. (2007) investigated composite cements containing up to 45% w/w steel slag. The steel slag fraction used was in the range of 0–5 mm. A wide range of tests were conducted on cement pastes and mortars, including initial and final setting times, standard consistency, flow of normal mortar, autoclave expansion and compressive strength. The authors conclude that “slag can be used in the production of composite cements of the strength classes 42.5 and 32.5 of EN 197-1. In addition, the slag cements present satisfactory physical properties. The steel slag slows down the hydration of the blended cements, due to the morphology of the contained $C_2S$ and its low content in calcium silicates”.

Shi and Hu (2003) indicated that steel slag has the potential to be used as a cementing product. However, he recommended that other materials to be combined with the steel slag to consume the free calcium in order to eliminate the propensity for expansion.

## 3. Research objective and scope of work

The main objective of this paper is to present the research results obtained on the use of steel slag, gravel and gabbro in concrete mixtures.

The emphasis of the work in the initial phase of this study was on the feasibility of utilizing steel slag and gravel aggregates in concrete, as a total or partial replacement of gabbro aggregate, used in construction in the State of Qatar by studying the properties of fresh and hardened concrete. Tests were conducted on concrete samples made of different aggregates to determine their acceptability for use in concrete. The different mixes were tested to determine compressive strength, splitting tensile strength, flexural strength, air content, and bulk density.

A total of nine concrete mixes were cast in the Department of Civil Engineering Laboratories at Qatar University. One concrete mix containing 100% gabbro aggregate was considered the control mix. Four concrete mixes containing 100%, 75%, 50%, and 25% steel slag (by weight) were prepared as partial replacements of gabbro aggregates. Another four concrete mixes containing 100%, 75%, 50%, and 25% gravel (by weight) were cast as partial replacements of gabbro aggregates.

## 4. Materials’ collection and mix proportioning

### 4.1. Cement

Cement used in this research work was Ordinary Portland Cement (OPC) produced by Qatar National Cement Company (QNCC). To minimize the storage time and other problems of bagged cement storage at the distribution sale market point, the cement was directly purchased from the QNCC through a special request. This brand of cement is the most widely available and used by the construction industry in the State of Qatar, as QNCC is the largest cement producer in Qatar.

### 4.2. Sand

Fine sand used in the research was washed sand known in Qatar as government wash sand, which was brought from the government sand washing plant. This sand was used in all concrete mixes prepared in the laboratories. The sand was tested in accordance with ASTM C33 to meet the specification requirements of concrete mixtures. Sieve analysis results for the sand are shown in Fig. 1 along with the upper and lower ASTM limits for each sieve size.

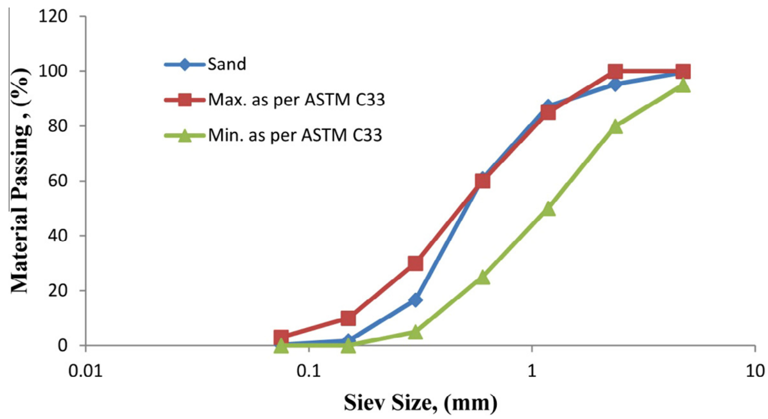


Figure 1. Sieve analysis envelope for normal concrete sand.

### 4.3. Aggregates

The three coarse aggregates used in this study were delivered by SAP. Gabbro, gravel, and steel slag were delivered in bags of approximately half cubic meter at different particle sizes. Five bags for each of the three materials, in five different particle size ranges of 0–2 mm, 2–5 mm, 5–10 mm, 10–15 mm, and 15–23 mm, were received at our laboratory.

#### 4.3.1. Gabbro

Gabbro is an aggregate type used by the construction industry in Qatar to replace the local limestone aggregate. These crushed dark stone particles are not produced in Qatar and they are barged mainly from the United Arab Emirates and the Sultanate of Oman in the form of coarse aggregates. This resulted in a surge in the cost of concrete products.

#### 4.3.2. Gravel

The gravel is naturally found in Qatar in significant quantities covered by a layer of weathered sand and soil. This layer of loose material ranges in thickness depending upon the type of parent soil and topography. Rocks are dogged out as a result of sand mines in the State of Qatar. These natural rounded stones are separated by size from the fine sand at the sand washing facility and then stored as a by-product. The stones are then sent to local quarries to be crushed as crushed stone aggregates.

#### 4.3.3. Slag

Steel slag aggregates are of an angular shape, with a rough surface and have a high bulk specific gravity in comparison with gravel or gabbro. The slag, used in our testing program, was aged in an open area for more than one year.

The fifteen bags (five for each aggregate type) received in five different particle sizes, ranging from 0–2 mm to 15–23 mm. In order to satisfy ASTM C33 standard, sampling of these materials was conducted to meet specification requirements. Sample blending was done for three different sample sizes(10, 20 and 40 kg). The blended aggregates were then tested in accordance with ASTM C33 to meet the specification requirements for a concrete mix. Sieve analysis results for these three blends are shown in Fig. 2 along with the upper and lower ASTM limits for each sieve size. Note that the three lines are plotted on top of each another.

## 5. Concrete mixture design

Nine trial concrete mixes were prepared in the Civil Engineering Laboratories. One concrete mix that contained 100% gabbro coarse aggregate was kept as the control mix (G20-100). Four concrete mixes containing 100%, 75%, 50%, and 25% as partial replacement of gabbro aggregate with slag aggregate, by weight were designated as S20-100, S20-75, S20-50 and S20-25, respectively. The second set of four concrete mixes containing 100%, 75%, 50%, and 25% partial replacement of gabbro aggregate with gravel aggregate, by weight was designated as GL20-100, GL20-75, GL20-50 and GL20-25, respectively.

The concrete mix design was proportioned to have a 28-day compressive strength of 30 MPa. The selection of this strength is based on industrial norms for normal structural concrete used in Qatar. The water-to-cement ratio (w/c of 0.58) was kept constant for all of the nine mixes in order to draw any meaningful comparisons. All concrete mixes were prepared without adding any admixtures or additives and thus more water will be needed to have workable mixes. Qatar Construction Standards (QCS) 2010-Section 5 specifies a slump (workability) of $125 \pm 40$ mm. Most of our slump measurements (Tables 1 and 2) were within this range. Details of the concrete mixture proportions of all mixes are given in Tables 1 and 2 for the steel slag and gravel aggregate mixtures, respectively.

## 6. Concrete samples' preparation

At the start, trial mixes were prepared. The ingredients (coarse aggregates, sand, cement, and water) were blended

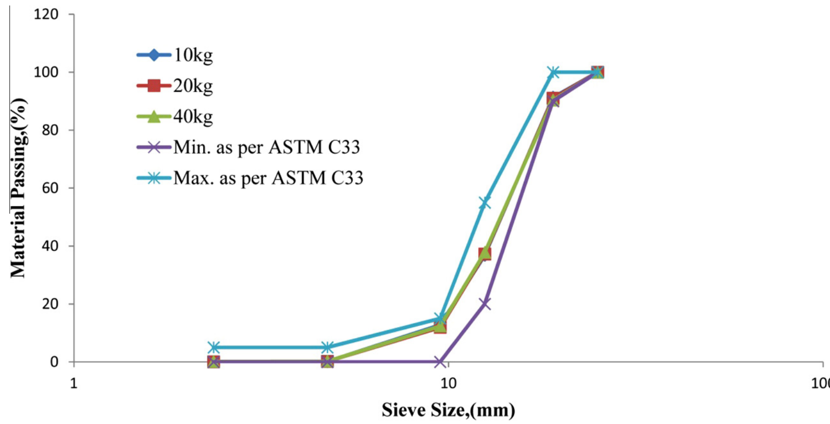


Figure 2. Sieve analysis envelope for aggregate size blend.

Table 1
Concrete mixture and test data for fresh concrete with steel slag.

| | Concrete mix | | | | |
|---|---|---|---|---|---|
| | G20-100 | S20-100 | S20-75 | S20-50 | S20-25 |
| Specified design strength (MPa) | 35 | 35 | 35 | 35 | 35 |
| Cement (kg) | 347.77 | 347.77 | 347.77 | 347.77 | 347.77 |
| Water (kg) | 201 | 201 | 201 | 201 | 201 |
| Sand (kg) | 709 | 709 | 709 | 709 | 709 |
| 20 mm Course aggregate(gabbro) | 1076 | 0 | 269 | 538 | 807 |
| 20 mm Course aggregate (slag) | 0 | 1076 | 807 | 538 | 269 |
| Slump (mm) | 80 | 70 | 70 | 80 | 80 |
| Air content (%) | 0.90 | 1.20 | 1.40 | 1.20 | 1.30 |
| Fresh concrete density (kg/m$^3$) | 2508.75 | 2705.29 | 2600.23 | 2578.40 | 2519.72 |
| Hardened concrete bulk density (kg/m$^3$) | 2428.97 | 2600.15 | 2552.23 | 2512.60 | 2465.50 |

Table 2
Concrete mixture and test data for fresh concrete with gravel.

| | Concrete mix | | | | |
|---|---|---|---|---|---|
| | G20-100 | GL20-100 | GL20-75 | GL20-50 | GL20-25 |
| Specified design strength (MPa) | 35 | 35 | 35 | 35 | 35 |
| Cement (kg) | 347.77 | 347.77 | 347.77 | 347.77 | 347.77 |
| Water (kg) | 201 | 201 | 201 | 201 | 201 |
| Sand (kg) | 709 | 709 | 709 | 709 | 709 |
| 20 mm Course aggregate (gabbro) | 1076 | 0 | 269 | 538 | 807 |
| 20 mm Course aggregate (gravel) | 0 | 1076 | 807 | 538 | 269 |
| Slump (mm) | 80 | 60 | 70 | 71 | 80 |
| Air content (%) | 0.90 | 1.15 | 1.20 | 1.20 | 1.10 |
| Fresh concrete density (kg/m$^3$) | 2508.75 | 2385.26 | 2414.92 | 2426.50 | 2467.46 |
| Hardened concrete bulk density (kg/m$^3$) | 2428.97 | 2327.90 | 2369.9 | 2373.60 | 2406.70 |

using an electric tilting-drum-type mixer having a 0.2 m$^3$ mixing capacity. For each mix, slump, unit weight and air content were determined for the fresh concrete; 150 mm × 300 mm cylinders and 200 mm × 800 mm beams were cast for later testing in accordance with ASTM C39, ASTM C496 and ASTM C78, respectively in order to determine the compressive strength, splitting tensile strength, and flexural strength of concrete at curing periods of 7, 28, and 90 days. Three specimens for each required test were cast and immersed after 24 h in water, until the time of test inside the laboratory at room temperature. A total of 246 concrete specimens were cast for the trial mixes; 162 cylindrical specimens (150 mm × 300 mm) and 84 beams (200 mm × 800 mm) were cast for the nine trial mixes and the designated tests. Fig. 3 shows photos of the electric mixer used in preparation and proportioning of specimens during their casting and curing in the water tank.

## 7. Testing

### *7.1. Uniaxial compressive strength test*

Uniaxial compressive strength test (Fig. 4) was carried out for all mixes at each curing period in accordance with

Figure 3. Portion of specimens during mixing, casting, and curing period.

ASTM C39. Three different cylinders for each mix were tested at each curing period. The average of the three test results was taken as the compressive strength value.

### 7.2. Splitting tensile strength test

The tensile strength (Fig. 5) is one of the basic and important properties of concrete. Concrete is not usually expected to resist direct tension because of its low tensile strength and brittle nature. However, the determination of tensile strength of concrete is necessary to determine the load at which the concrete members may crack. The splitting tensile strength was performed in accordance with ASTM C496 on three cylinders of each mix at each curing period.

### 7.3. Flexural test

The ability of a beam or slab to resist failure in bending is a measure of the flexural strength. The flexural strength of concrete is about 12–20% of compressive strength. Flexural strength is useful for field control and acceptance of concrete pavements. To determine the flexural strength of concrete (ASTM C78), three beams were cast and tested


Figure 4. Test set-up for uniaxial compressive strength test.


Figure 5. Set-up for splitting tensile strength test.

under four point loading for each trial mix at each curing period. Test set-up is shown in Fig. 6.

## 8. Results

The fresh concrete data showed that the mix with 100% gravel aggregates (GL20-100) recorded the lowest slump value at 60 mm, and the control mix which contained 100% gabbro aggregates (G20-100) had a slump of 80 mm at the same water-to-cement ratio of 0.58. This is believed to be due to the rounded shape and smooth texture of the gravel aggregates. It is known in concrete science that aggregates' surface texture and shape influence the bond and stress level at which microcracking starts. Surface texture also affects the strength by virtue of that crushed rock, such as gabbro and slag, which will lead to higher concrete strengths because of better mechanical interlocking between the cement paste and the aggregates. Slump (see Table 1) for the steel slag concrete mix with 100% slag aggregate (S20-100), was 70 mm. Both concrete mixes (steel slag and gravel aggregates) showed an increase in slump (see Tables 1 and 2) with an increase in gabbro aggregate content used in the mixes, and slump eventually increased to the controlled mix slump value of 80 mm.

The unit weight of fresh concrete made of 100% steel slag aggregates (S20-100) recorded the highest value of all mixes at 2705 kg/m$^3$ while the concrete mix made of 100% gravel aggregate (GL20-100) recorded the lowest value of 2385 kg/m$^3$. The control mix which contained 100% gabbro aggregates (G20-100) had a unit weight of 2508 kg/m$^3$. The unit weight decreases with an increase in the percentage of gabbro aggregate used in mixes containing steel slag aggregates, while it increases with an increase in the percentage of gabbro aggregates used in mixes containing gravel aggregates.

Hardened concrete specimens were crushed in the laboratory at the designated curing periods depending on the mixing dates of the specimens. Results obtained from specific test are discussed in detail later in the paper. After the completion of each test, samples were stored temporarily in the laboratory for later verification of failure mode and test reliability. Fig. 7 shows photos of the crushed concrete samples.

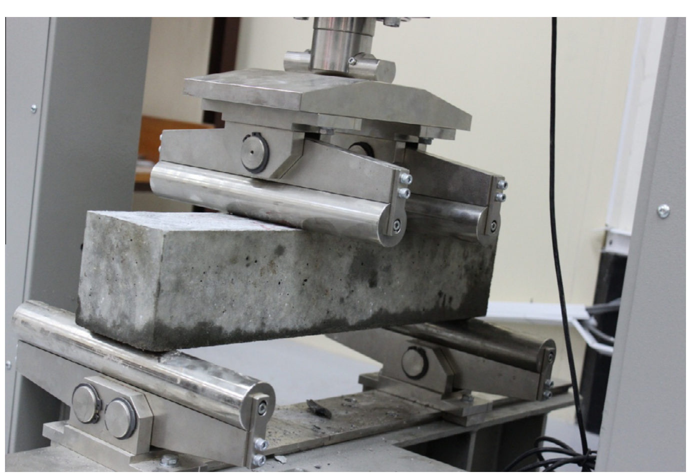

Figure 6. Test set-up for the flexural test.

### 8.1. Compressive strength

Compressive strengths of different concrete mixes after 7, 28 and 90 days of curing are presented in Tables 3 and 4 for steel slag and gravel concrete mixes, respectively. The test data indicate that all the nine mixes had average 28-day compressive strengths greater than 30 MPa. The compressive strength was found to increase with age for all concrete mixes, even after 90 days of curing in the water tank.

The compressive strength of concrete containing steel slag aggregates increased with an increase in percentage of slag aggregates in the mix. The 28-day compressive strength reached a maximum value of 43.88 MPa with 100% steel slag aggregate (S20-100) and a minimum value of 38.62 MPa for the mix with 25% steel slag aggregate (S20-25). This value of 43.88 MPa for the 100% steel slag aggregate mix indicates an increase of 11% gain in compressive strength compared to the compressive strength for the control mix (0% slag). The concrete mix with the minimum steel slag aggregate of 25% (S20-25) gave an average 28-day compressive strength of 38.62 MPa, which is within the 1% of the control mix. Fig. 8 shows the compressive strength data versus curing time for all mixes. The data indicate that there is a clear indication of better performance of steel slag aggregate concrete mixes over the control mix in-terms of compressive strength.

Concrete containing gravel coarse aggregates on the other hand yielded a lower compressive strength at 100% gravel content (GL20-100) when compared with the

Figure 7. Photos of crushed concrete samples from various tests.

Table 3
Compressive strength data for concrete made with steel slag.

| Test age (days) | Compressive strength (150 mm × 300 mm cylinder) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | G20-100 | | S20-100 | | S20-75 | | S20-50 | | S20-25 | |
| | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) |
| 7 | 24.2 | **21.85** | 23.76 | **22.47** | 35.1 | **34.56** | 31.3 | **31.07** | 30.3 | **30.05** |
| 7 | 18.8 | | 22.83 | | 533.5 | | 930.4 | | 229.5 | |
| 7 | 22.6 | | 20.83 | | 534.98 | | 831.34 | | 130.32 | |
| 28 | 36.95 | **39.19** | 44.2 | **43.88** | 43.1 | **42.86** | 41.1 | **39.25** | 38.6 | **38.62** |
| 28 | 40.62 | | 343.6 | | 942.5 | | 438.4 | | 238.7 | |
| 28 | 40.19 | | 843.74 | | 742.87 | | 438.17 | | 438.51 | |
| 90 | 42.61 | **44.76** | 49.4 | **49.43** | 50.7 | **50.49** | 48.5 | **48.34** | 47.6 | **46.38** |
| 90 | 42.95 | | 646.7 | | 650.4 | | 149.5 | | 643.2 | |
| 90 | 48.73 | | 852.05 | | 550.26 | | 147.01 | | 348.26 | |

Table 4
Compressive strength data for concrete made with gravel.

| Test age (days) | Compressive strength (150 mm × 300 mm cylinder) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | G20-100 | | GL20-100 | | GL20-75 | | GL20-50 | | GL20-25 | |
| | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) |
| 7 | 24.2 | **21.85** | 26.97 | **26.25** | 26.6 | **26.77** | 27.37 | **27.82** | 26.84 | **27.43** |
| 7 | 18.8 | | 26.39 | | 27.31 | | 28.52 | | 26.92 | |
| 7 | 22.6 | | 25.40 | | 26.39 | | 27.58 | | 28.53 | |
| 28 | 36.95 | **39.19** | 35.41 | **33.91** | 35.35 | **35.60** | 36.40 | **37.68** | 35.94 | **36.35** |
| 28 | 40.62 | | 33.35 | | 36.30 | | 37.40 | | 36.81 | |
| 28 | 40.19 | | 32.97 | | 35.14 | | 39.24 | | 36.31 | |
| 90 | 42.61 | **44.76** | 34.8 | **37.55** | 47.9 | **41.55** | 41.4 | **41.150** | 40.86 | **42.60** |
| 90 | 42.95 | | 240.3 | | 442.6 | | 240.8 | | 40.96 | |
| 90 | 48.73 | | 837.46 | | 440.46 | | 828.6* | | 45.97 | |

control mix (Fig. 9). The maximum 28-day compressive strength for this mix was 33.91 MPa, which gave a reduction of 14% when compared to the compressive strength of the control mix. This is believed to be due to the smooth texture and rounded shape of the gravel particles. Aggregates such as gabbro and slag will lead to higher concrete strengths because of their rough textures, which will lead to better mechanical interlocking between the cement paste and the aggregates. The blended mixtures' compressive strengths increased with the addition of gabbro aggregates until it reached a maximum value of 37.68 MPa for 50/50% blend mix of gravel and gabbro aggregates (GL20-50). The maximum compressive strength for this mix was still shy of reaching 39.19 MPa obtained for the control mix and found to be about 4% lower at 28-day curing.

### 8.2. Splitting tensile strength

The splitting tensile strengths for all mixes are shown in Tables 5 and 6 for concrete made with steel slag and gravel aggregates, respectively. The 7, 28 and 90-day splitting tensile strengths are depicted graphically in Figs. 10 and 11 for steel slag and gravel aggregates, respectively. The data indicate that there is an increase in the tensile strength with age for all mixes. However, the tensile strength data tend to level off after 90 days of curing.

Concrete mixes with slag aggregates showed a range increase from 11% for 100% steel slag to 1% for 25% slag in comparison with the control mix at the 28-day age. These percent increases in the tensile strength are in agreement with the results obtained from the compressive strength tests. The concrete mixes with 100% gravel aggregates, however, showed a decrease in the splitting tensile strength at 28-day of age compared to the control mix. The 100% gravel mix gave a value of 2.877 MPa, which was 15% lower than that of the control mix. The 28-day tensile strength showed an increase with an increase in gabbro content in the mix, however, at its maximum value of 3.257 MPa it was still short of about 6% from the control mix. Fig. 11 illustrates this finding, where it clearly shows the gradual increase in the tensile strength with a decrease in gravel content.

### 8.3. Flexural strength

The 7, 28 and 90-day flexural strength test results are presented in Tables 7 and 8 for the steel slag- and gravel-concrete mixes, respectively. The data showed an increase in the flexural strength with age for all mixes. It was

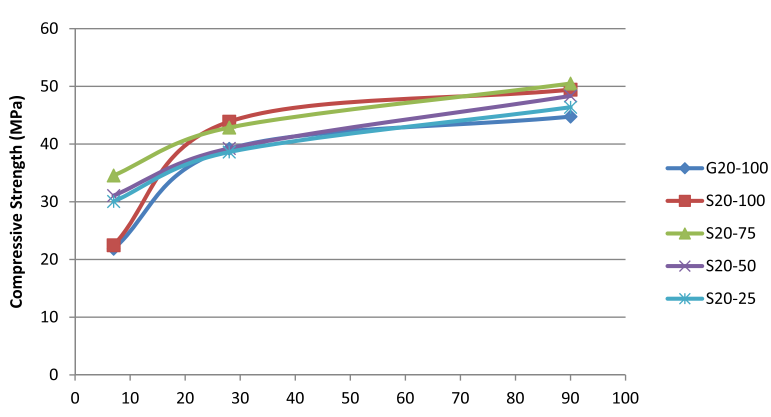


Figure 8. Compressive strength for different slag-concrete mixes.

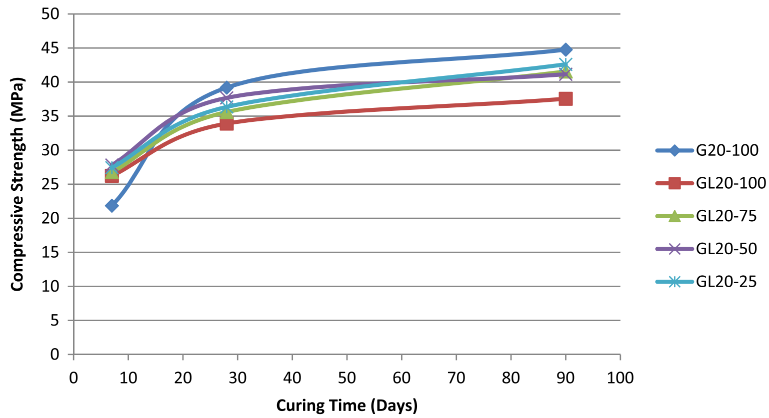


Figure 9. Compressive strength for different gravel-concrete mixes.

Table 5
Splitting tensile strength data for hardened concrete made with slag.

| Test age (days) | Splitting tensile strength (150 mm × 300 mm cylinder) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | G20-100 | | S20-100 | | S20-75 | | S20-50 | | S20-25 | |
| | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) |
| 7 | 2.686 | **2.882** | 3.067 | **2.991** | 3.120 | **3.108** | 2.740 | **2.897** | 2.777 | **2.922** |
| 7 | 3.087 | | 3.064 | | 3.329 | | 2.950 | | 2.929 | |
| 7 | 2.875 | | 2.843 | | 2.876 | | 3.000 | | 3.059 | |
| 28 | 3.265 | **3.408** | 3.798 | **3.796** | 3.783 | **3.363** | 3.745 | **3.625** | 3.182 | **3.457** |
| 28 | 3.359 | | 3.579 | | 3.016 | | 2.781* | | 3.404 | |
| 28 | 3.600 | | 4.011 | | 3.291 | | 3.625 | | 3.786 | |
| 90 | 3.426 | **3.48** | 3.176 | **3.87** | 3.548 | **3.71** | 3.460 | **3.52** | 3.341 | **3.68** |
| 90 | 3.564 | | 3.82 | | 3.587 | | 3.636 | | 3.764 | |
| 90 | 3.466 | | 3.925 | | 3.996 | | 3.587 | | 3.961 | |

Table 6
Splitting tensile strength data for hardened concrete made with gravel.

| Test age (days) | Splitting tensile strength (150 mm × 300 mm cylinder) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | G20-100 | | GL20-100 | | GL20-75 | | GL20-50 | | GL20-25 | |
| | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) |
| 7 | 2.686 | **2.882** | 2.785 | **2.717** | 2.380 | **2.325** | 2.480 | **2.731** | 2.576 | **2.488** |
| 7 | 3.087 | | 2.687 | | 2.453 | | 2.944 | | 2.635 | |
| 7 | 2.875 | | 2.680 | | 2.142 | | 2.770 | | 2.253 | |
| 28 | 3.265 | **3.408** | 2.938 | **2.877** | 3.186 | **3.155** | 3.181 | **3.232** | 3.205 | **3.257** |
| 28 | 3.359 | | 2.795 | | 3.251 | | 3.185 | | 3.309 | |
| 28 | 3.600 | | 2.897 | | 3.028 | | 3.330 | | 3.257 | |
| 90 | 3.426 | **3.485** | 3.661 | **3.478** | 3.280 | **3.106** | 3.479 | **3.470** | 2.73* | **3.350** |
| 90 | 3.564 | | 3.400 | | 1.97* | | 3.46 | | 3.396 | |
| 90 | 3.466 | | 3.372 | | 2.932 | | 2.834 | | 3.304 | |

observed from the test results that the flexural strengths for both of the concrete mixes (S20-100 and GL20-100) surpass that of the control mix (G20-100) at the 28-day curing period. The flexural strength results for slag- and gravel-concrete mixes are depicted in Figs. 12 and 13, respectively.

Mixes containing steel slag aggregates showed respective increases of 12.8% and 12.6% in the 28-day flexural strengths for concrete containing 100% and 75% steel slag in comparison with the control mix. The other two mixes prepared using 50% and 25% steel slag came within the 1% range. Gravel-concrete mixes, however, did not show any significant increase or decrease in flexural strengths, except for the 100% mix (GL20-100) which resulted in a 9% increase in flexural strength in comparison with the control mix.

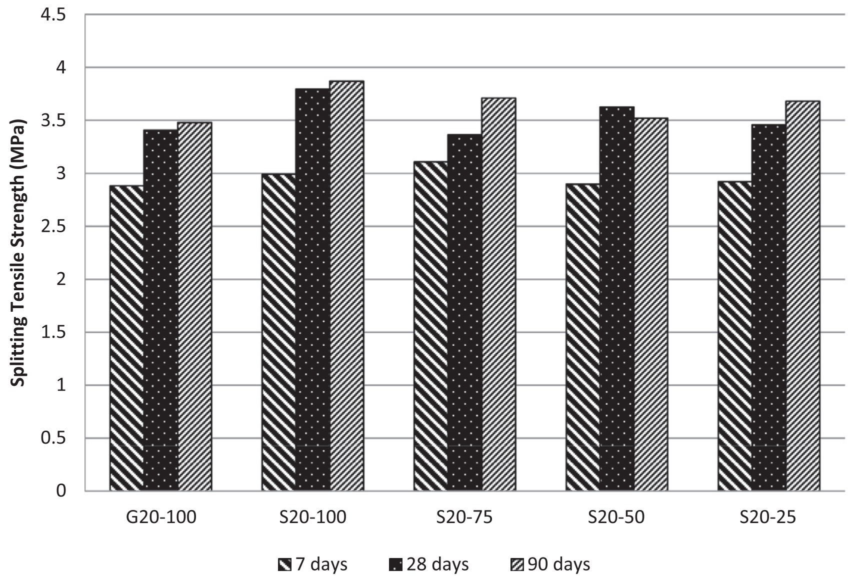


Figure 10. Splitting tensile strength for different slag-concrete mixes.

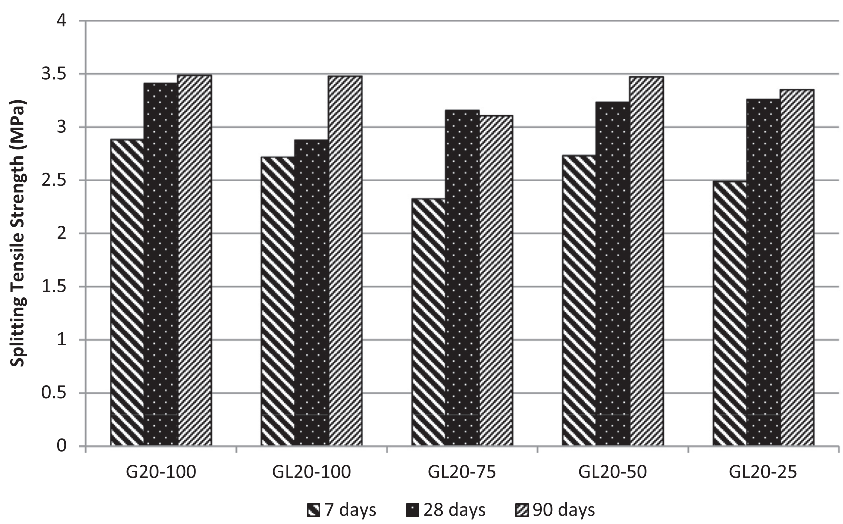


Figure 11. Splitting tensile strength for different gravel-concrete mixes.

Table 7
Flexural data for hardened concrete made with steel slag.

| Test age (days) | Flexural strength | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | G20-100 | | S20-100 | | S20-75 | | S20-50 | | S20-25 | |
| | Actual (MPa) | Average (Mpa) | Actual (MPa) | Average (Mpa) | Actual (MPa) | Average (Mpa) | Actual (MPa) | Average (Mpa) | Actual (MPa) | Average (Mpa) |
| 7 | 3.357 | **4.133** | 4.411 | **4.546** | 4.487 | **4.302** | 3.875 | **4.072** | 3.631 | **3.681** |
| 7 | 3.935 | | 4.698 | | 4.415 | | 4.149 | | 3.657 | |
| 7 | 5.108 | | 4.530 | | 4.005 | | 4.191 | | 3.755 | |
| 28 | 4.560 | **4.585** | 5.300 | **5.175** | 4.685 | **5.163** | 4.903 | **4.517** | 4.650 | **4.494** |
| 28 | 4.387 | | 4.969 | | 5.769 | | 4.330 | | 3.518 | |
| 28 | 4.808 | | 5.257 | | 5.036 | | 4.317 | | 5.313 | |
| 90 | 5.187 | **5.346** | 6.016 | **6.178** | 5.604 | **5.834** | 5.517 | **5.501** | 5.298 | **5.187** |
| 90 | 5.259 | | 6.127 | | 6.196 | | 5.648 | | 4.643 | |
| 90 | 5.593 | | 6.390 | | 5.701 | | 5.337 | | 5.620 | |

Table 8
Flexural strength data for hardened concrete made with gravel.

| Test age (days) | Flexural strength | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | G20-100 | | GL20-100 | | GL20-75 | | GL20-50 | | GL20-25 | |
| | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) | Actual (MPa) | Average (MPa) |
| 7 | 3.357 | **4.133** | 3.500 | **3.103** | 3.392 | **3.475** | 4.020 | **3.964** | 4.057 | **3.883** |
| 7 | 3.935 | | 2.738 | | 3.818 | | 3.933 | | 3.707 | |
| 7 | 5.108 | | 3.071 | | 3.216 | | 3.940 | | 3.886 | |
| 28 | 4.560 | **4.585** | 5.126 | **5.034** | 4.305 | **4.279** | 4.569 | **4.647** | 4.919 | **4.482** |
| 28 | 4.387 | | 5.015 | | 4.295 | | 4.779 | | 3.944 | |
| 28 | 4.808 | | 4.959 | | 4.236 | | 4.593 | | 4.581 | |
| 90 | 5.187 | **5.346** | 5.329 | **5.662** | 5.929 | **5.817** | 5.517 | **5.501** | 4.926 | **5.501** |
| 90 | 5.259 | | 5.763 | | 5.705 | | 5.648 | | 5.728 | |
| 90 | 5.593 | | 5.895 | | 5.816 | | 5.337 | | 5.849 | |

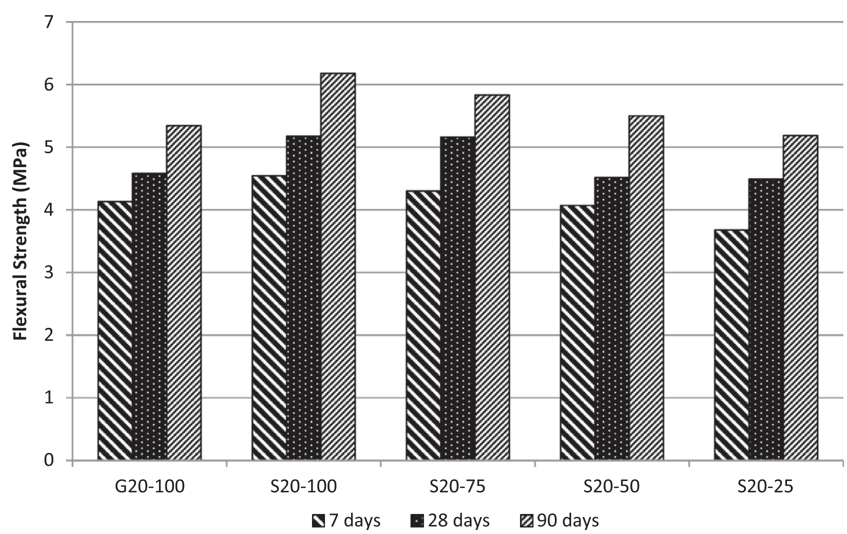


Figure 12. Flextural strength for different slag-concrete mixes.

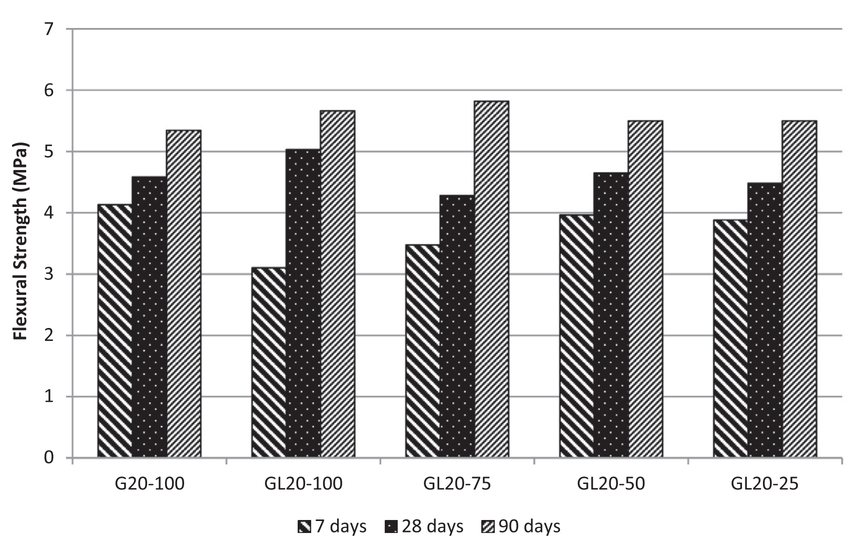


Figure 13. Flextural strength for different gravel-concrete mixes.

## 9. Conclusions and recommendations

### 9.1. Conclusions

The 7, 28 and 90-day compressive strength, splitting tensile strength and flexural strength data obtained for concrete prepared using 100% steel slag aggregates yielded better results than the control mixture (concrete made with 100% gabbro). Concrete cast using 100% gravel, on the other hand, yielded lower strength results than the control mixture. However, there was an increase in strength values with an increase in gabbro content in gravel/gabbro blends. All concrete mixtures prepared easily met the 28-day compressive strength design requirement of 30 MPa. Concrete cured for 90 days in the water tank did not exhibit any reversal in strength.

### 9.2. Recommendations

Additional work is necessary to establish long-term performance, especially concerning what is reported in the literature about the expansive characteristics of steel slag aggregates when used in concrete.


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