SELF-COMPACTING CONCRETE WITH GROUND FERRONICKEL SLAG AS SUPPLEMENTARY CEMENTITIOUS MATERIAL

MD NURUZZAMAN and PRABIR KUMAR SARKER

School of Civil & Mechanical Engineering, Curtin University, Perth, Australia

Ferronickel slag (FNS) is a by-product of the smelting of nickel ore. When ground to powder, it can be used to partially replace ordinary Portland cement (OPC). This study focused on the production of self-compacting concrete (SCC) by replacing OPC with 20%, 35%, and 50% ground ferronickel slag (GFNS). In addition, natural sand was replaced by FNS in all the mixtures. Thus, the significance of this research is the conservation of natural resources by the dual use of FNS and GFNS. The fresh properties of SCC were evaluated as per EFNARC. The results show that the concrete mixtures using FNS and GFNS together met the criteria of SCC. Concrete microstructure was investigated by SEM images, and a detailed phase assemblage was studied by XRD. The highest 28 days compressive strength was found as 68 MPa in the mixture with 35% GFNS. The 50% cement replacement by GFNS showed the lowest compressive strength among all the mixes. The splitting tensile strength results followed a similar development as compressive strength. Hence, it implies that FNS can be a potential eco-friendly material that can be used in the production of SCC.

Keywords: Nickel, Portland cement, Compressive strength, Microstructure.

1 INTRODUCTION

Carbon dioxide emissions from cement manufacturing are well known. Therefore, scientists have spent a considerable time in the last several decades to discover supplementary cementitious material (SCM). On this purpose, they studied fly ash, blast furnace slag, silica fume, steel slag, copper slag, metakaolin, sugarcane bagasse ash, rice husk, ladle furnace slag, and so on (Das et al. 2007, Berndt 2009). Das et al. (2007) found that blast furnace slag when used as an SCM in concrete, lowers the required hydration heat while maintaining or improving the material's strength and durability. However, another industrial by-product, known as ferronickel slag (FNS), is produced in electric arc furnaces at very high temperatures (Choi and Choi 2015). Due to the low nickel content in the ores, an enormous amount of slag is produced during the smelting process (Saha and Sarker 2018). The physical features of FNS make it ideal to use it in concrete as a fine aggregate, as shown in previous studies (Sakoi et al. 2013, Saha et al. 2018). On the other hand, Rahman et al. (2017) used 50% GFNS in mortar as cement substitute and reported an unaltered setting time with slightly reduced water demand. Moreover, when FNS was used in self-compacting concrete (SCC), the workability reduced while the compressive strength increased with increased FNS content (Nuruzzaman et al. 2020). Again, nanoindentation test confirmed that SCC can be produced sustainably by using GFNS (Nuruzzaman et al. 2023c). However, the combined effect of FNS and GFNS in SCC is very scarce in existing literature.
The manufacture of one ton of nickel alloy results in the release of around 12 to 14 tons of FNS as a by-product (Saha and Sarker 2016) which needs space, manpower, and materials for proper disposal. As a result, the use of this slag has high potential to bring sustainability to the concrete industry while cutting down on the cost of disposal. Nonetheless, it is crucial to study the immediate and future effects of each additional substance on the characteristics of concrete. Therefore, the purpose of this study was to find the consequence of using FNS and GFNS in SCC.

2 MATERIALS AND METHODS

2.1 Materials

In this research, crushed granite of bulk density 1465 kg/m$^3$ (Nuruzzaman et al. 2022) was used as the coarse aggregate. The fine aggregate was made up of 60% sand and 40% FNS for all the mixes. The particle size distributions of FNS and sand are provided in Figure 1. From the graph, it is apparent that the FNS particles are larger than the sand. Thus, their combination provided an improved well-graded fine aggregate. The chemical compositions of the binders are given in Table 1. Abundances of CaO, SiO$_2$ and Al$_2$O$_3$ are observed in OPC and SiO$_2$, MgO, and Fe$_2$O$_3$ in GFNS. MasterRheobuild 1000 was also used as a superplasticizer in all the mixes.

![Figure 1. Particle size distribution curve of fine aggregates.](image)

Table 1. Chemical compositions of OPC (Nuruzzaman *et al.* 2023a) and GFNS (Kuri *et al.* 2023).

| Materials (%) | CaO | SiO$_2$ | Al$_2$O$_3$ | MgO | Fe$_2$O$_3$ | Na$_2$O | K$_2$O | SO$_3$ | FeO$_3$ | TiO$_2$ | ZnO | Cr$_2$O$_3$ | SrO | LOI$^a$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>63.11</td>
<td>20.29</td>
<td>5.48</td>
<td>1.24</td>
<td>2.85</td>
<td>0.29</td>
<td>0.45</td>
<td>2.49</td>
<td>0.17</td>
<td>0.27</td>
<td>0.04</td>
<td>0.02</td>
<td>0.05</td>
<td>3.39</td>
</tr>
<tr>
<td>GFNS</td>
<td>0.48</td>
<td>51.42</td>
<td>2.88</td>
<td>30.58</td>
<td>12.85</td>
<td>0.08</td>
<td>0.03</td>
<td>0.05</td>
<td>0.01</td>
<td>0.06</td>
<td>0.02</td>
<td>1.07</td>
<td>&lt;0.01</td>
<td>-</td>
</tr>
</tbody>
</table>

2.2 Concrete Mixture Compositions

To investigate the impact of GFNS in SCC, four different mixtures were studied by varying the amount of GFNS. GFNS replaced OPC by volume at a rate of 20, 35, and 50%, where the control specimen had no GFNS. The designation of the mixtures is given according to this replacement percentage. The mix proportions are provided in Table 2. The mixtures were cast, stored, and cured at ambient temperature. For curing, lime water was used.

2.3 Methodology

In this study, for fresh properties, slump flow, T$_{50}$, J-ring, V-funnel, V-funnel$_{5min}$, L-box and U-box tests were carried out as per the European Federation of National Associations Representing for Concrete (EFNARC). Compressive strength test as per ASTM C39 (ASTM 2014) and splitting tensile test as per ASTM C496 (ASTM 2017) were conducted to determine the hardened concrete
properties. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) test was performed to understand the microstructure.

Table 2. Mix proportions (kg/m$^3$) (Nuruzzaman et al. 2023b).

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Binder</th>
<th>Fine aggregate</th>
<th>Coarse aggregate</th>
<th>Water</th>
<th>SP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OPC</td>
<td>GFNS</td>
<td>Sand</td>
<td>FNS</td>
<td></td>
</tr>
<tr>
<td>F40GF0</td>
<td>572</td>
<td>0</td>
<td>547</td>
<td>438</td>
<td>706</td>
</tr>
<tr>
<td>F40GF20</td>
<td>458</td>
<td>107</td>
<td>547</td>
<td>438</td>
<td>706</td>
</tr>
<tr>
<td>F40GF35</td>
<td>372</td>
<td>188</td>
<td>547</td>
<td>438</td>
<td>706</td>
</tr>
<tr>
<td>F40GF50</td>
<td>286</td>
<td>268</td>
<td>547</td>
<td>438</td>
<td>706</td>
</tr>
</tbody>
</table>

3 RESULTS AND DISCUSSIONS

3.1 Conformity of Fresh Properties to the Requirements of SCC

The results of the fresh properties of SCC mixes are given in Table 3. The slump flow values for F40GF0, F40GF20, F40GF35, and F40GF50 are 660, 685, 730, and 755 mm, respectively. Thus, with the intensification of GFNS, workability of the mixture improved. The T$_{50}$ value varied from 4 to 3 seconds. The EFNARC (2002) recommended limits for SCC are 650 to 850 mm of flow diameter and 2 to 5 seconds of T$_{50}$. However, during the tests, it was visually confirmed that a further increase in GFNS would cause segregation. The J-ring height difference values varied from 10 to 3 mm, which are within the EFNARC limit. The J-ring spread value increased from 615 mm to 740 mm with the rise of GFNS from zero to 50%, which followed the trend of slump flow values. The EFNARC recommended limit of the V-funnel flow time is 6 to 12 seconds, and the V-funnel$_{5min}$ limit is another extra 3 seconds from the flow time. As shown in Table 3, the V-funnel test results of the mixtures varied from 9 to 6 seconds, whereas the V-funnel$_{5min}$ results varied from 11 to 8 seconds. The L-box results ranged from 0.86 to 0.96, whereas the standard range was from 0.8 to 1. The height difference in the U-box test varied from 15 mm to 4 mm. The standard limit of EFNARC is from 0 to 30 mm. Therefore, all the fresh concrete mixtures were in compliance with EFNARC's recommendation. Furthermore, the results are clearly indicative that GFNS increases the workability of concrete.

Table 3. Fresh properties (Nuruzzaman et al. 2023b).

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Slump flow</th>
<th>J-ring</th>
<th>V-funnel</th>
<th>V-funnel$_{5min}$</th>
<th>L-box</th>
<th>U-box</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dia (mm)</td>
<td>T$_{50}$ (sec)</td>
<td>Dia (mm)</td>
<td>Time (sec)</td>
<td>Time (sec)</td>
<td>(H$_2$-H$_1$)</td>
</tr>
<tr>
<td>F40GF0</td>
<td>660</td>
<td>4</td>
<td>10</td>
<td>615</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>F40GF20</td>
<td>685</td>
<td>4</td>
<td>9</td>
<td>655</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>F40GF35</td>
<td>730</td>
<td>3</td>
<td>5</td>
<td>710</td>
<td>7</td>
<td>8.5</td>
</tr>
<tr>
<td>F40GF50</td>
<td>755</td>
<td>3</td>
<td>3</td>
<td>740</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

3.2 Compressive and Tensile Strength

Concrete's compressive strength is its most important mechanical property. The horizontal bar chart displays these compressive test results in Figure 2(a). At both the ages, the control specimens show the highest compressive strength, and the 50% replacement mixture F40GF50 shows the lowest strength. The gradual decrease of the compressive strength can be endorsed to the gradual decrease of OPC in the binder system. This is likely to have arisen from the differences in amounts of CaO in the binders since OPC has a very high CaO content, while GFNS has a negligible amount of it (Table 1). As a result, when GFNS increases, the amount of CaO decreases accordingly in the
binder. This might restrict the production of CS-type hydrates and thus affect the compressive strength. However, the strength escalated by 31.5%, 34.9%, 33.5%, and 54.5% from 7 days to 28 for F40GF0, F40GF20, F40GF35 and F40GF50, respectively. The pozzolanic behavior of GFNS and the significant amount of silica content in GFNS explain this strength improvement. More calcium-silicate-hydrate, the prime strength contributing hydration product, might be formed when the additional silica reacts with calcium hydroxide. However, Ibnu et al. (2019) reported that by substituting 20% OPC with GFNS, the 28-day compressive strength declined by around 20% from the compressive strength of conventional concrete. While in this research, in self-compacting concrete, this reduction is around 15% for the same replacement level. Therefore, the result obtained from this investigation supports the existing literature.

![Figure 2](image_url)

**Figure 2.** Strength of SCC, (a) compressive, (b) tensile.

In this research, tensile strength was determined by splitting tensile tests of different mixtures at the age of 28 days. Figure 2(b) shows the experimental and predicted tensile strength of different mixes. Prediction of the tensile strengths was determined by following AS 3600 (Standards Australia 2009) and ACI 318 (ACI Committee 318 2008). The highest tensile strength is found to be 5.48 MPa for the control specimen and the lowest to be 3.51 MPa for F40GF50. The pattern of tensile strength resembles the result of compressive strength. But Zhou and Shi (2022) reported that in massive high-strength concrete, replacing 30 to 40% OPC by GFNS increased the 28 days splitting tensile strength slightly. From the Figure 2(b), it is clear that for the mixes F40GF0, F40GF20, and F40GF35, the experimental value is higher than the predicted values by both AS 3600 and ACI 318, but for F40GF50 the experimental value is slightly lower than the predicted ones. So, it can be said that the lab-tested tensile strengths are compatible with the predicted results; thus, existing design equation can be used to predict the tensile strength.

### 3.3 Microstructural Analysis

The surface topography was analyzed by SEM. The SEM micrographs for F40GF0, F40GF20, F40GF35, and F40GF50 are given in Figure 3. Control specimen F40GF0 appears to have a more compact surface morphology, with fewer voids and cracks based on the images. For F40GF20 and F40GF35, the voids and cracks are relatively higher than in the control specimen. And for F40GF50, the number of voids and micro-cracks are highest among the specimens. Thus, the heterogeneity and porous nature of SCC specimens are explained by the increased amount of GFNS. These micrographs endorse the compressive and tensile strength results. With the help of XRD, the mineral phases present in the specimens were identified. A typical XRD spectrum for
mixture F40GF35 is provided in Figure 3(e). Except for quartz, a good amount of fluorite was also identified. This fluorite is nothing but the internal standard material mixed externally with the powder sample during the sample preparation for XRD. In addition to these minerals, anorthite, calcite, calcium silicate hydrate, enstatite, forsterite, pargasite, and portlandite phases were also detected. However, forsterite found in the XRD pattern was one of the most important results in this research. Because it implies that the FNS and GFNS sourced Mg did not take participation in the hydration process, rather remained unaltered in the form of forsterite ferroan. Crystalline form of Mg might be the reason for this, which did not disintegrate during hydration process.

This finding is in agreement with the result of Rahman et al. (2017) that highly stable forsterite is present in GFNS raw material, which does not participate in hydration. However, no trace of Ca(OH)₂ or brucite formation was found. As a result, there is no adverse expansion in concrete volume, despite the high Mg concentration of GFNS. The results reported by Yang et al. (2014) also supports this volume stability. The authors stated that since the production of GFNS involves high temperatures in the pyrometallurgical process, it is much less reactive than normal MgO.

3 CONCLUSION

The fresh, mechanical, and microstructural characteristics of GFNS-incorporated SCC were investigated in this research. Some of the broad conclusions drawn from the results are:

- Self-compacting properties of concrete can be achieved by substituting natural sand by 40% and ordinary Portland cement by up to 50% GFNS without any blocking or segregation.
- The test results of fresh concrete properties confirm that with the increase of GFNS content, the workability of the SCC increases.
- In response to an increase in GFNS in the binder matrix, both compressive strength and tensile strength decrease. A decrease of 16% in compressive strength was recorded when the substitution level was 35%, which is considered compatible and the low calcium of GFNS contributes to this finding.
- Microstructural investigation confirms that detrimental brucite was not present in the reaction product. The excess magnesium present in FNS remains in stable forsterite ferroan crystalline form and does not take part in the hydration process.
References

ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary, American Concrete Institute, Farmington Hills, MI, USA, 2008.


