MECHANICAL PERFORMANCE OF ALKALI-ACTIVATED CONCRETE INCORPORATING RECYCLED AGGREGATES AND STEEL FIBERS

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This study evaluates the mechanical performance of alkali-activated concrete cured at ambient conditions and made with recycled aggregates (RA) and steel fibers. The precursor binder was either ground granulated blast furnace slag or a blend of slag and fly ash (3:1 and 1:1). The alkaline activator solution was a blend of sodium hydroxide and sodium silicate. Coarse aggregates were either natural aggregates (NA) or RA, while fine aggregates comprised desert dune sand. Steel fibers were incorporated, in 2%, by volume, in RA-based concrete mixes. Results showed that replacing NA by 100% RA in plain alkali-activated slag concrete led to decreases of 21, 23, and 51% in compressive, tensile splitting, and flexural strengths, respectively. Meanwhile, alkali-activated slag-fly ash blended (3:1 and 1:1) mixes experienced respective losses of up to 65, 50, and 57%. The corresponding properties of alkali-activated counterparts made with 100% RA increased by up to 172, 273, and 167% upon the addition of 2% steel fibers, by volume. Yet, the impacts of RA and steel fiber incorporation on the mechanical properties were more pronounced in concrete mixes having higher fly ash replacement. Alkali-activated slag and slag-fly ash blended concrete mixes incorporating 2% steel fibers, by volume, and 100% RA exhibited equivalent compressive strength and superior tensile splitting and flexural strengths to those of NA-based counterparts.

Keywords: Performance evaluation, Slag, Fly ash, Alkali-activation.

1 INTRODUCTION

Concrete structures are typically demolished at the end of their service life. The produced construction and demolition waste (CDW) are disposed of in stockpiles and landfills, posing a serious environmental challenge to the construction industry. As a means of sustainable waste management, this waste concrete can be recycled in the form of recycled aggregates (RA). In addition to its ability to alleviate concrete-induced environmental pollution, it can relieve the stress on natural resources to produce natural aggregates (NA) and alleviate its carbon dioxide (CO₂) footprint (Radonjanin et al. 2013, Alzard et al. 2021). Comparably, cement has been replaced with supplementary cementitious materials to mitigate anthropogenic emissions attributed to its production. In the case of complete replacement of cement, the precursor binding agent, slag or fly ash, is chemically activated in an alkaline solution and is depicted as a geopolymer or alkali-activated material (Davidovits 1991, Zhang et al. 2020, Amer et al. 2021,
Najm et al. 2021). Given their advantages, the integration of RA and alkali-activated materials promises to be an optimal solution to the environmental challenges of concrete.

Previous work has examined the ability to replace NA with RA in alkali-activated slag and fly ash geopolymer concrete (Hu et al. 2019, Xie et al. 2019, Huang et al. 2021). Results from these studies showed that the RA replacement reduced the mechanical properties and durability of so-produced concrete. A similar reduction in performance was reported in conventional cement-based concrete. As such, researchers had resorted to incorporating steel fibers into cement-based RA concrete mixes (Gao and Zhang 2018, Ali and Qureshi 2019, Kachouh et al. 2019, Kachouh et al. 2020, Kachouh et al. 2021). However, such an approach has received limited attention in alkali-activated concrete. Hence, this study aims to examine the mechanical properties of alkali-activated slag-fly ash (1:0, 3:1, and 1:1) blended concrete made with 100% RA and incorporating 2% steel fibers, by volume, through the compressive, tensile splitting, and flexural strengths.

2 MATERIALS

Ground granulated blast furnace slag (referred to hereafter as slag) and fly ash were used as precursor binding materials. Slag was chemically composed of calcium oxide (CaO) and silicon dioxide (SiO₂) with respective Blaine fineness and specific of 4250 cm²/g and 2.50. Contrarily, the fly ash was made of silicon dioxide and aluminum oxide with respective Blaine fineness of 3680 cm²/g and 2.32. Their chemical composition, gradation, and microstructure is reported elsewhere (El-Hassan and Elkholy 2021).

Natural aggregates (NA) and recycled aggregates (RA) served as the coarse aggregates, whereas natural dune sand (DS) was used as fine aggregates. The NA was crushed limestone with a 20-mm nominal maximum size. Meanwhile, RA, with the same NMS, was acquired from a local recycling facility after crushing CDW from old concrete. Both coarse aggregates were added to the mix after reaching a saturated surface dry (SSD) state. Their particle size distributions and properties are shown in other work (Kachouh et al. 2019).

The alkaline activator solution (AAS) was formulated by combining sodium silicate (SS) and sodium hydroxide (SH). The grade-N SS solution had respective chemical compositions of SiO₂, Na₂O, and H₂O of 26.3, 10.3, and 63.4%, by mass. Conversely, the SH solution was formulated to a molarity of 14 M by adding 97-98% purity sodium hydroxide flakes in tap water. Such a molar concentration was adopted based on past studies (Patankar et al. 2014, Sani et al. 2016, El-Hassan and Ismail 2018). In addition, a polycarboxylic-based superplasticizer (SP) was incorporated into the alkali-activated concrete to enhance the workability without impacting the mechanical performance, as suggested elsewhere (Palacios and Puertas 2005, Montes et al. 2012).

To enhance the mechanical properties of alkali-activated concrete mixes made with RA, double hooked-end steel fibers (SF) were incorporated into the mix in 2% volume fraction. The mean diameter, mean length, tensile stress, and Young’s modulus were 0.55 mm, 35 mm, 1345 MPa, and 210000 MPa, respectively.

3 METHODOLOGY

3.1 Mix Design

Table 1 presents the mix design of alkali-activated concrete. Nine concrete mixes were proportioned to assess the impact of NA replacement by RA and incorporation of steel fibers on the mechanical properties of alkali-activated slag-fly ash blended concrete. Mixes were denoted as SaRbFc, where a, b, and c denoted the percent of slag in the total binding material, percent RA replacement, and steel fiber volume fraction, respectively. Slag was replaced by 0, 25, and 50%
fly ash, by mass. For the first three mixes representing the NA-based control mixes, the binder, solution, and aggregate contents were formulated to obtain a 30-MPa cylinder compressive strength at 28 days ($f'_c$). The same mix design was utilized in the residual groups of mixes while replacing 100% NA by RA and adding 2% steel fiber, by volume.

### Table 1. Mix design of alkali-activated concrete mixes (kg/m$^3$).

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Mix Designation</th>
<th>Slag</th>
<th>Fly Ash</th>
<th>DS</th>
<th>NA</th>
<th>RA</th>
<th>SS</th>
<th>SH</th>
<th>SP</th>
<th>SF</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>S100R0F0</td>
<td>300.0</td>
<td>0.0</td>
<td>725</td>
<td>1210</td>
<td>0</td>
<td>99</td>
<td>66</td>
<td>7.50</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>S75R0F0</td>
<td>187.5</td>
<td>62.5</td>
<td>765</td>
<td>1220</td>
<td>0</td>
<td>99</td>
<td>66</td>
<td>6.25</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>S50R0F0</td>
<td>125.0</td>
<td>125.0</td>
<td>910</td>
<td>1137</td>
<td>0</td>
<td>90</td>
<td>60</td>
<td>5.00</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>S100R100F0</td>
<td>300.0</td>
<td>0.0</td>
<td>725</td>
<td>0</td>
<td>1210</td>
<td>99</td>
<td>66</td>
<td>7.50</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>S75R100F0</td>
<td>187.5</td>
<td>62.5</td>
<td>765</td>
<td>0</td>
<td>1220</td>
<td>99</td>
<td>66</td>
<td>6.25</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>S50R100F0</td>
<td>125.0</td>
<td>125.0</td>
<td>910</td>
<td>0</td>
<td>1137</td>
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<td>60</td>
<td>5.00</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>S100R100F2</td>
<td>300.0</td>
<td>0.0</td>
<td>725</td>
<td>0</td>
<td>1210</td>
<td>99</td>
<td>66</td>
<td>7.50</td>
<td>156</td>
</tr>
<tr>
<td>8</td>
<td>S75R100F2</td>
<td>187.5</td>
<td>62.5</td>
<td>765</td>
<td>0</td>
<td>1220</td>
<td>99</td>
<td>66</td>
<td>6.25</td>
<td>156</td>
</tr>
<tr>
<td>9</td>
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<td>125.0</td>
<td>910</td>
<td>0</td>
<td>1137</td>
<td>90</td>
<td>60</td>
<td>5.00</td>
<td>156</td>
</tr>
</tbody>
</table>

#### 3.2 Sample Preparation

Alkali-activated concrete ingredients were mixed using a laboratory shear mixer under ambient conditions (temperature of 23±2°C and relative humidity of 50±5%). The alkaline solution was formulated 24 hours before casting to release the heat associated with the exothermic reactions. At the time of mixing and casting, the coarse and fine aggregates, slag, and fly ash were thoroughly mixed for 3 minutes. In mixes 7, 8, and 9, the steel fibers were included with the binder and aggregates to properly disperse them. The SP was incorporated into the alkaline solution, which was, in turn, steadily added to the mix and mixed for 3 more minutes to homogenize the mixture. Fresh alkali-activated concrete was cast into 100 mm diameter x 200 mm height cylinders and 100 mm height x 100 mm width x 500 mm length prisms, compact-vibrated on a vibrating table, and sealed for 24 hours with plastic wrap. Subsequently, concrete samples were removed from their molds and left in open air until testing.

#### 3.3 Performance Evaluation

The 28-day cylinder compressive strength, tensile splitting strength, and flexural strength of alkali-activated concrete were determined following ASTM C39, C496, and C78, respectively (ASTM 2015, ASTM 2011, ASTM 2016). Three samples were evaluated for each mix and test.

#### 4 RESULTS AND DISCUSSION

##### 4.1 Compressive Strength

Figure 1 shows the 28-day cylinder compressive strength of alkali-activated slag-fly ash blended concrete. The control mixes, having 100% NA (S100R0F0, S75R0F0, S50R0F0), had respective $f'_c$ values of 31.8, 31.5, and 29.7 MPa. Their respective total binder content was 300, 250, and 250 kg/m$^3$, while the AAS-to-binder ratio was 0.55, 0.65, and 0.60. This shows that less binder is required to attain similar compressive strength results, highlighting the superior performance of slag-fly ash blended concrete to slag-based counterparts. Past research noted that such a blend of binders accelerated the activation reaction and densified the matrix through the formation of calcium aluminosilicate hydrate (C-A-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gels (Chi 2012, Al-Majidi et al. 2016, Ismail and El-Hassan 2018, El-Hassan and Elkholy 2019).
Furthermore, replacing NA by 100% RA reduced the values of $f'_c$ of control mixes made with slag-to-fly ash ratios of 1:0, 3:1, and 1:1 by 21, 50, and 65%, respectively. Such a loss in performance is owed to the porous nature of the RA and the weak bond at the new paste-old mortar interface (Kachouh et al. 2019). However, despite having the same binder content in mixes made with 25 and 50% fly ash, the reduction in $f'_c$ was more prominent in mixes with higher fly ash content, possibly due to a weak bond between the alkali-activated paste and RA. A similar impact of fly ash replacement has been noted elsewhere (El-Hassan et al. 2021a).

The inclusion of 2% steel fiber volume fraction in 100% RA alkali-activated concrete mixes increased the compressive strength. Indeed, $f'_c$ of mixes made with 100% slag, 75:25 slag-to-fly ash ratio, and 50:50 slag-to-fly ash ratio increased by 20, 102, and 172%, respectively, owing to the bridging effect of steel fibers and their ability to limit crack development and propagation. Results also show that the extent of improvement in $f'_c$ is more pronounced in mixes with higher fly ash replacements that are associated with a weak binding matrix even though a similar binder content was employed in the latter two mixes. Compared to the control mixes, steel fiber-reinforced mixes sustained a limited loss (< 5%) in $f'_c$. A similar finding was noted upon reinforcing cement-based RA concrete with steel fibers (Kachouh et al. 2019). This highlights steel fibers’ ability to counteract the negative impact of RA replacement on $f'_c$. As such, it is possible to fully replace NA by RA in alkali-activated slag-fly ash concrete mixes upon including 2% steel fiber volume fraction while maintaining comparable compressive strength.

4.2 Tensile Splitting Strength

The 28-day tensile splitting strength ($f_{sp}$) of alkali-activated concrete is presented in Figure 2(a). While mixes made with 1:0 and 3:1 slag-to-fly ash ratio had similar $f_{sp}$ values, that of mix S50R0F0 was 25% lower. This decrease is aligned with that of compressive strength and is owed to a weaker binding matrix (El-Hassan et al. 2021b). The replacement of NA by RA resulted in up to 47% lower $f_{sp}$, with higher reductions being noted for mixes made with more fly ash. Apparently, RA replacement was less detrimental on $f_{sp}$ than $f'_c$. Nevertheless, its effect was countered by steel fiber inclusion. In fact, adding 2% steel fibers, by volume, led to increases in $f_{sp}$ of 164, 192, and 260% for RA mixes made with 0, 25, and 50% fly ash, respectively. As such, alkali-activated concrete can be designed with 100% RA and 2% steel fiber volume fraction with superior tensile properties than NA-based mixes.

4.3 Flexural Strength

The 28-day flexural strength ($f_r$) results of alkali-activated concrete are shown in Figure 2(b). The replacement of 25% slag by fly ash did not have an impact on $f_r$, whereas a higher
replacement of 50% reduced $f_r$ by 44%. Such reduction is aligned with that of $f_{sp}$ and $f'_c$. Furthermore, 100% RA replacement reduced $f_r$ of mixes made with 0, 25, and 50% fly ash by 51, 53, and 57%, respectively. However, this negative impact of RA was offset by steel fiber addition. For the three alkali-activated RA-based concrete mixes, the inclusion of 2% steel fiber addition, by volume, increased $f_r$ by 162, 109, and 167%, respectively. Compared to the NA-based control mixes, those incorporating 100% RA and 2% steel fiber, by volume, had equivalent or superior flexural properties. Kachouh et al. (2020) reported similar results in cement-based RA concrete.

![Figure 2](image-url) (a) Splitting tensile and (b) flexural strength of 28-day alkali-activated concrete mixes.

5 CONCLUSIONS

This paper examines the mechanical properties of alkali-activated concrete made with recycled aggregate and steel fibers. Test results highlighted respective decreases of up to 65, 47, and 57% in the compressive, tensile splitting, and flexural strengths of alkali-activated concrete upon NA replacement by RA, with higher reductions being noted for mixes incorporating more fly ash. Such loss in performance was owed to the rough and porous nature of the RA and the weak interfacial bond between the new alkali-activated binding paste and the old mortar. Nevertheless, the inclusion of 2% steel fiber volume fraction in 100% RA mixes increased the corresponding strengths by up to 172, 260, and 167%. Compared to the NA-based control mixes, they experienced equivalent or superior mechanical properties. This performance enhancement was associated with the bridging effect of steel fibers and their ability to hinder the crack development and propagation.

Acknowledgments

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References


