Performance of Steel Fiber-Reinforced Alkali-Activated Slag-Fly Ash Blended Concrete Incorporating Recycled Concrete Aggregates and Dune Sand

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Abstract: This study evaluates the performance of alkali-activated slag-fly ash blended concrete made with recycled concrete aggregates (RCA) and reinforced with steel fibers. Two blends of concrete with ground granulated blast furnace slag-to-fly ash ratios of 3:1 and 1:1 were used. Natural aggregates were substituted with RCA, while macro steel fibers with 35 mm of length and aspect ratio of 65 were incorporated in RCA-based mixtures at various volume fractions. Fine aggregates were in the form of desert dune sand. Mechanical and durability characteristics were investigated. Experimental results revealed that RCA replacement decreased the compressive strength of plain concrete mixtures with more pronounced reductions being perceived at higher replacement percentages. Mixtures made with 30%, 70%, and 100% RCA could be produced with limited loss in the design compressive strength upon incorporating 1%, 2%, and 2% steel fibers, by volume, respectively. In turn, splitting tensile strength was comparable to the NA-based control while adding at least 1% steel fiber, by volume. Moreover, higher water absorption and capillary sorptivity and lower ultrasonic pulse velocity, bulk resistivity, and abrasion resistance were reported during RCA replacement. Meanwhile, incorporation of steel fibers densified the concrete and enhanced its resistance to abrasive forces, water permeation, and water transport. Analytical regression models were developed to correlate hardened concrete properties to the 28-day cylinder compressive strength.

Keywords: alkali-activated concrete; slag; fly ash; steel fibers; dune sand; recycled concrete aggregate; hardened properties; analytical regression model

1. Introduction

The management of construction and demolition wastes (CDW) is a global critical matter. The excessive quantities of waste generated through the construction, demolition, and renovation of infrastructures and superstructures are extending the capacity of landfills and causing economic losses [1]. For example, the European Union, the United States of America, and the Republic of China have been producing over 800, 500, and 200 million tons of CDW annually, respectively [2–5]. Yet, only 20% of this material is recycled [6–8]. To mitigate the production of these wastes, alleviate the pressing need for landfill sites, and reduce the consumption of natural resources, CDW has been proposed to be recycled [6–8]. The utilization of this sustainable waste management solution has been reported to have the capacity to reduce the environmental footprint of the construction industry [9,10]. Indeed, over the past few decades, CDW has been recycled and reutilized in the form of recycled concrete aggregates (RCA) and served to replace natural aggregates (NA) in various construction applications. Such a concrete is composed of 65–70% virgin aggregate and 30–35% original cementitious paste, by volume [11]. Despite its economic and environmental benefits, the adoption of RCA for structural applications has been hindered, owing to its inferior mechanical and durability properties compared to those of NA-based conventional concrete [12–15].
The environmental sustainability of concrete products can also be improved by reducing the consumption of cement. In fact, the production of cement is responsible for 5–7% of the global greenhouse gas emissions and is inducing an increase in the concentration of atmospheric carbon dioxide gas [16–19]. As such, its manufacturing process is becoming a global ecological, environmental, and social burden. Thus, it is imperative that more sustainable alternatives are utilized to alleviate the negative impacts of cement. Partial cement replacement by supplementary cementitious materials and pozzolans, including fly ash, ground granulated blast furnace slag (or simply slag), silica fume, metakaolin, and others, has been found to maintain or even improve the characteristics of concrete while reducing the negative impacts associated with cement production. However, complete replacement of cement in concrete that undergoes typical hydration reactions is not feasible due to the significant reduction in performance. Rather, these sustainable materials can be used as the sole precursor binders to produce inorganic alkali-activated polymers or “geopolymers” [20].

Past research on geopolymer or alkali-activated concrete has reported comparable or superior characteristics to ordinary Portland cement (OPC) concrete [21–28], rendering it a suitable and sustainable alternative. Among the different binding materials used, a blend of slag and fly ash has been reported to provide excellent mechanical and durability performance while eliminating the need for heat curing and reducing age-related microcrack development [25,29–35]. Such exceptional performance is primarily owed to the denser microstructure, which typically consists of an intermix of calcium aluminosilicate hydrate (C-A-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gels [25,29,33,35–37]. However, it was concluded that the fly ash percentage of the total binder was not to exceed 50% because of its slow activation reaction in ambient conditions, which may negatively affect the properties of the alkali-activated concrete. Furthermore, previous studies compared the interfacial bond between aggregates and each of OPC and alkali-activated binders [38,39]. Results showed that the bond was stronger when the latter was employed. As such, alkali-activated binders could be a better binder than OPC in concrete made with RCA. Indeed, the performance of alkali-activated concrete incorporating RCA has been investigated in the literature. Inferior mechanical and durability characteristics were reported for RCA-based alkali-activated concrete compared to the NA-based counterparts, owing to the poor properties of RCA relative to those of NA [40–47]. Such findings hinder its adoption by the construction industry.

Analogous loss in performance has been reported in conventional OPC concrete due to NA replacement by RCA. To counter this challenge, various techniques were adopted, of which fiber incorporation seemed most promising [48–55]. The addition of up to 2% steel fibers, by volume, in concrete mixtures made with OPC and RCA resulted in increases in the compressive strength, critical strain, toughness, modulus of elasticity, abrasion resistance, and flexural properties and decreases in the shrinkage, sorptivity, and water absorption [48,50–54]. In fact, steel fiber-reinforced OPC RCA concrete showed comparable or better performance to plain counterparts made with NA [48,50–54]. Furthermore, the inclusion of micro carbon fibers in alkali-activated mortars incorporating fine recycled aggregates showed an improvement in the mechanical properties [56]. Accordingly, it seems that incorporation of fibers in alkali-activated concrete made with RCA is promising to restore the properties. However, the ability of steel fibers to improve the performance of alkali-activated slag-fly ash blended concrete made with RCA is yet to be investigated.

This research aims to fill this research gap by examining the performance of ambient-cured alkali-activated activated ground granulated blast furnace slag (referred to hereafter as slag) fly ash blended concrete made with RCA and reinforced with macro steel fibers. The plain concrete mixtures were proportioned to obtain a 30-MPa design cylinder compressive strength. The slag-to-fly ash ratio was set to 3:1 and 1:1 to assess the degree of reduction and improvement in performance due to respective RCA replacement and steel fiber incorporation as a function of slag and fly ash contents. Further, the purpose of using both precursors was to eliminate the need for heat curing associated with fly
ash-based geopolymers and reduce the drying shrinkage cracks related to alkali-activated slag composites. The RCA replacement, by mass, was 30%, 70%, or 100% steel fibers based on the slag and fly ash contents used. Fine aggregates were in the form of desert dune sand as a means of contributing towards sustainable development. The alkaline activator solution was a mixture of grade N sodium silicate and sodium hydroxide with a molarity of 14 M. RCA-based concrete mixtures were reinforced with 0%, 1%, and 2% steel fibers, by volume, to promote the full replacement of NA by RCA without compromising the performance. The steel fiber volume fraction was limited to 2%, as preliminary trial mixtures with higher volume fractions could not be properly cast. The mechanical properties of alkali-activated slag-fly ash blended concrete made with steel fibers and RCA were evaluated, including compressive strength, compressive stress-strain behavior, modulus of elasticity, and splitting tensile strength. Their durability characteristics were assessed through the water absorption, sorptivity, ultrasonic pulse velocity, bulk resistivity, and abrasion resistance tests. Analytical relationships correlating the different hardened concrete properties were developed. This study provides a state-of-the-art material characterization of alkali-activated slag-fly ash blended concrete incorporating RCA and reinforced with steel fibers. Results of the present study are anticipated to play a vital role towards utilization of this concrete in structural applications.

2. Materials

2.1. Precursor Binders

The precursor binding materials were slag and fly ash. Their chemical compositions were obtained using X-ray fluorescence (XRF) and are presented in Table 1. While the slag was predominantly made of calcium oxide (CaO) and silica (SiO₂), the fly ash mainly comprised silica (SiO₂) and alumina (Al₂O₃). Their respective Blaine fineness were 4250 and 3680 cm²/g, whereas their corresponding specific gravity were 2.50 and 2.32. Furthermore, Figure 1 highlights their particle size distribution. The respective particle sizes of slag and fly ash were in the ranges of 2–80 µm and 0.2–40 µm. The morphologies of the as-received binding materials using scanning electron microscopy are presented in Figure 2. Spherical and irregular particles were noticed in fly ash and slag micrographs, respectively. The X-ray diffraction (XRD) patterns of Figure 3 show that the binders comprised of quartz and mullite with traces of gehlenite and hematite in slag and fly ash, correspondingly.

Table 1. Chemical composition and physical properties of slag, fly ash, and dune sand.

| Oxides          | Slag (%) | Fly Ash (%) | Dune Sand (%) |
|-----------------|----------|-------------|---------------|
| CaO             | 42.0     | 3.3         | 14.1          |
| SiO₂            | 34.7     | 48.0        | 64.9          |
| Al₂O₃           | 14.4     | 23.1        | 3.0           |
| MgO             | 6.9      | 1.5         | 1.3           |
| Fe₂O₃           | 0.8      | 12.5        | 0.7           |
| Loss on ignition| 1.1      | 1.1         | 0.0           |
| Others          | 0.2      | 10.5        | 16.0          |

Physical properties

| Property                  | Slag (cm²/g) | Fly Ash (cm²/g) | Dune Sand (cm²/g) |
|---------------------------|--------------|-----------------|-------------------|
| Blaine Fineness           | 4250         | 3680            | -                 |
| Specific gravity          | 2.50         | 2.32            | 2.77              |

2.2. Fine Aggregates

Locally abundant desert dune sand served as the fine aggregates. Its fineness modulus, dry-rodded density, specific gravity, and surface area were 1.45, 1663 kg/m³, 2.77, and 116.8 cm²/g, respectively. The grading curve of dune sand, shown in Figure 1, indicates that most of the particles are within the range of 100–600 µm. Compared to a conventional ASTM C33 [57] sand, dune sand particle size is finer. Figures 2c and 3c present the
respective SEM micrograph and XRD spectrum of dune sand. It is mainly composed of irregular particles representing quartz with some traces of calcite, ferric oxide, and aluminum oxide.

![Particle Size Distribution](image1.png)

**Figure 1.** Particle size distribution of slag, fly ash, and dune sand.

![SEM Micrographs](image2.png)

**Figure 2.** SEM micrographs of (a) slag, (b) fly ash, and (c) dune sand.

![XRD Patterns](image3.png)

**Figure 3.** XRD patterns of (a) slag, (b) fly ash, and (c) dune sand.

### 2.3. Coarse Aggregates

Coarse aggregates were NA and RCA. The NA was in the form of crushed dolomitic limestone with a nominal maximum size (NMS) of 20 mm. Conversely, the RCA was collected from a local recycling plant that recycled construction and demolition waste from old concrete structures with an unknown compressive strength. RCA was not chemically or mechanically treated at the plant. Its NMS was also 20 mm. Figure 4 shows the grading curves for different mixtures of NA and RCA used in this study. It is worth noting that they all satisfy the requirements and limits of ASTM C33 [57]. Moreover, the physical properties of NA and RCA are summarized in Table 2. The water absorption, Los Angeles (LA) abrasion mass loss, soundness mass loss, and fineness modulus of the latter were higher than the former, while the specific gravity and dry-rodded density were lower. This
signifies that RCA has indeed a weaker nature than NA. Also, it is worth noting that all measured properties were within the typical limits given by the ASTM standards [58–61] except for water absorption, which exceeded the limits. As such, the water absorption was offset by achieving a saturated surface dry (SSD) state of aggregates before incorporating them into the concrete mixture.

![Particle size distribution of different mixtures of NA and RCA.](image)

Figure 4. Particle size distribution of different mixtures of NA and RCA.

| Property                     | Unit     | Standard Test       | NA       | RCA       | Dune Sand |
|------------------------------|----------|---------------------|----------|-----------|-----------|
| Dry-rodded density           | kg/m³    | ASTM C29 [62]       | 1635     | 1563      | 1663      |
| Absorption                   | %        | ASTM C127 [63]      | 0.22     | 6.63      | -         |
| Los Angeles abrasion         | %        | ASTM C131 [61]      | 16.0     | 32.6      | -         |
| Surface area                 | cm²/g    | ASTM C136 [64]      | 2.49     | 2.50      | 116.80    |
| Soundness (MgSO₄)           | %        | ASTM C88 [58]       | 1.20     | 2.78      | -         |
| Specific gravity             | -        | ASTM C127 [63]      | 2.72     | 2.53      | 2.67      |
| Fineness modulus             | -        | ASTM C136 [64]      | 6.82     | 7.44      | 1.45      |

### 2.4. Alkaline Activator Solution and Superplasticizer

To activate the precursor binding materials, an alkaline activator solution (AAS) was formulated as a mixture of sodium silicate (SS) and sodium hydroxide (SH). The SS solution was Grade N with a density of 1380 kg/m³ and a chemical composition of 26.3% SiO₂, 10.3% Na₂O, and 63.4% H₂O. Conversely, the SH solution was prepared by dissolving 97%-pure SH flakes in a specific amount of water to obtain a molarity of 14 M and a density of 1506 kg/m³. This molarity was chosen based on past research that optimized the reaction efficiency for superior mechanical and durability performance [34,65–67]. Yet, it should be noted that the SH solution was prepared 24 h prior to casting to allow for the heat associated with the exothermic reaction to dissipate. Furthermore, a polycarboxylic ether polymer-based superplasticizer (SP) with a specific gravity of 1.2 was employed to maintain adequate fresh concrete workability without affecting the mechanical properties [68,69].

### 2.5. Steel Fibers

Double hooked-end macro steel fibers (referred to hereafter as steel fibers) with 35 mm of length and aspect ratio of 65 were employed in this study. The physical properties of the steel fibers were obtained from the manufacturer and are summarized in Table 3 [70]. Trial mixtures with more than 2% steel fiber, by volume, could not be cast. As such, the highest steel fibers volume fraction used was set to 2%. 
Table 3. Properties of steel fibers (as provided by the manufacturer [70]).

| Material      | $d_f$ (mm) | $l_f$ (mm) | Aspect Ratio ($l_f/d_f$) | Density (g/cm$^3$) | Fiber Network (Fiber/kg) | $f_t$ (MPa) | $E_f$ (GPa) |
|---------------|------------|------------|--------------------------|--------------------|-------------------------|-------------|-------------|
| Steel fibers  | 0.55       | 35         | 65                       | 7.9                | 14.531                  | 1345        | 210         |

3. Methods

3.1. Mixture Proportioning

The mixture proportions of alkali-activated slag-fly ash blended concrete mixtures are shown in Table 4. A total of twenty mixtures were proportioned to assess the influence of varying the slag-to-fly ash ratio, RCA replacement percentage, and steel fibers volume fraction on the performance of alkali-activated slag-fly ash blended concrete. Mixture designations were developed by SxRyFz, where x, y, and z represent the percentage of slag relative to the total binder mass, RCA mass replacement percentage, and steel fibers volume fraction, respectively. The plain NA-based control mixtures (S75R0F0 and S50R0F0) were designed using trial and error to attain a 28-day cylinder compressive strength ($f'_c$) of 30 MPa assuming 3% air content. Such design strength is typical for normal-strength concrete structures. The purpose of using both precursor binders was to eliminate the need for heat curing associated with fly ash-based geopolymer and reduce the drying shrinkage cracks related to alkali-activated slag composites. Such a blended system has a potential to enhance the performance of geopolymer concrete due to the co-existence of calcium aluminosilicate hydrate (C-A-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gels [25,36,71]. It is also worth noting that increasing the fly ash content beyond 50% was found to be detrimental to the properties of ambient-cured alkali-activated concrete [25]. Therefore, the slag replacement by fly ash was set to 25% and 50%.

Table 4. Mix proportions of alkali-activated slag concrete mixtures.

| Mix No. | Mix Designation | Slag (kg) | Fly Ash (kg) | DS $^1$ | NA $^1$ | RCA $^1$ | SS $^1$ | SH $^1$ | SP $^1$ | SF $^1$ | Mass (kg) | Volume (m$^3$) |
|---------|-----------------|---------|-------------|--------|--------|--------|--------|--------|--------|--------|-----------|---------------|
| 1       | S75R0F0         | 187.5   | 62.5        | 765    | 1220   | 0      | 99     | 66     | 6.25   | 0      | 187.5      | 0.99          |
| 2       | S75R30F0        | 187.5   | 62.5        | 765    | 854    | 366    | 99     | 66     | 6.25   | 0      | 187.5      | 1.00          |
| 3       | S75R30F1        | 187.5   | 62.5        | 765    | 854    | 366    | 99     | 66     | 6.25   | 78     | 187.5      | 1.01          |
| 4       | S75R30F2        | 187.5   | 62.5        | 765    | 854    | 366    | 99     | 66     | 6.25   | 156    | 187.5      | 1.02          |
| 5       | S75R70F0        | 187.5   | 62.5        | 765    | 366    | 854    | 99     | 66     | 6.25   | 0      | 187.5      | 1.01          |
| 6       | S75R70F1        | 187.5   | 62.5        | 765    | 366    | 854    | 99     | 66     | 6.25   | 78     | 187.5      | 1.02          |
| 7       | S75R70F2        | 187.5   | 62.5        | 765    | 366    | 854    | 99     | 66     | 6.25   | 156    | 187.5      | 1.03          |
| 8       | S75R100F0       | 187.5   | 62.5        | 765    | 0      | 1220   | 99     | 66     | 6.25   | 0      | 187.5      | 1.02          |
| 9       | S75R100F1       | 187.5   | 62.5        | 765    | 0      | 1220   | 99     | 66     | 6.25   | 78     | 187.5      | 1.03          |
| 10      | S75R100F2       | 187.5   | 62.5        | 765    | 0      | 1220   | 99     | 66     | 6.25   | 156    | 187.5      | 1.04          |
| 11      | S50R0F0         | 125.0   | 125.0       | 910    | 1210   | 0      | 90     | 60     | 5.00   | 0      | 125.0      | 1.03          |
| 12      | S50R30F0        | 125.0   | 125.0       | 910    | 847    | 346    | 90     | 60     | 5.00   | 0      | 125.0      | 1.03          |
| 13      | S50R30F1        | 125.0   | 125.0       | 910    | 847    | 346    | 90     | 60     | 5.00   | 78     | 125.0      | 1.04          |
| 14      | S50R30F2        | 125.0   | 125.0       | 910    | 847    | 346    | 90     | 60     | 5.00   | 156    | 125.0      | 1.05          |
| 15      | S50R70F0        | 125.0   | 125.0       | 910    | 363    | 798    | 90     | 60     | 5.00   | 0      | 125.0      | 1.03          |
| 16      | S50R70F1        | 125.0   | 125.0       | 910    | 363    | 798    | 90     | 60     | 5.00   | 78     | 125.0      | 1.04          |
| 17      | S50R70F2        | 125.0   | 125.0       | 910    | 363    | 798    | 90     | 60     | 5.00   | 156    | 125.0      | 1.05          |
| 18      | S50R100F0       | 125.0   | 125.0       | 910    | 0      | 1137   | 90     | 60     | 5.00   | 0      | 125.0      | 1.03          |
| 19      | S50R100F1       | 125.0   | 125.0       | 910    | 0      | 1137   | 90     | 60     | 5.00   | 78     | 125.0      | 1.04          |
| 20      | S50R100F2       | 125.0   | 125.0       | 910    | 0      | 1137   | 90     | 60     | 5.00   | 156    | 125.0      | 1.05          |

$^1$ Note: DS = dune sand; NA = natural aggregates; RCA = recycled concrete aggregates; SS = sodium silicate; SH = sodium hydroxide; SP = superplasticizer; SF = steel fibers.

For mixtures 2–10, a 3:1 slag-to-fly ash ratio was used with slag and fly ash contents of 187.5 and 62.5 kg/m$^3$, respectively. Dune sand content was kept constant at 765 kg/m$^3$. The NA was replaced by 30%, 70%, and 100% RCA, by mass. The AAS-to-binder ratio was fixed at 0.66 with an SS-to-SH ratio of 1.5. Superplasticizer was added as 2.5% of
the total binder mass, while steel fibers were incorporated between 0 and 2%, by volume. Furthermore, the slag-to-fly ash ratio was 1:1 for mixtures 12–20. The total binder content was 250 kg/m\(^3\) with an AAS-to-binder mass ratio of 0.60 and superplasticizer dosage of 2%, by binder mass. Also, the dune sand and coarse aggregates were set to 910 and 1210 kg/m\(^3\), respectively. Similar to mixtures 2–10, the steel fibers in mixtures 12–20 varied from 0 to 78 and 156 kg/m\(^3\), representing 0 to 1% and 2% volume fractions. As shown in Table 4, the variations in the specific gravity of NA and RCA and the addition of steel fibers are not of great influence, as negligible changes in the volume of the mix were noted. Such negligible changes in the volume have also been reported in previously published literature \[27,53,72\].

3.2. Sample Preparation

Alkali-activated slag-fly ash blended concrete was prepared and cast in the laboratory at respective temperature and relative humidity of 23 °C ± 2 °C and 50% ± 5%. The pre-prepared SH solution was first mixed with the SS solution to formulate the AAS. The heat from the reaction was allowed to dissipate before incorporating into the mixture. The dry components, comprising NA and/or RCA, dune sand, fly ash, and slag were mixed for 3 min in a pan mixer. Steel fibers, where used, were added to the dry components to properly disperse in the mixture. The superplasticizer was added to the prepared AAS, and the wet components were gradually added to the dry components and mixed for another 3 min to attain a homogeneous and uniform mixture. The obtained freshly-mixed concrete was cast in two layers into 100 mm × 200 mm (diameter × height) cylinders and 100-mm cubes and compact-vibrated on a vibrating table for 5–10 s in accordance with ASTM C192 \[73\]. Compacted concrete samples were covered with a plastic sheet for 24 h at ambient conditions, then demolded and kept in ambient conditions until testing age. Three replicate samples per mixture were prepared for each experimental test.

3.3. Performance Evaluation

The cube compressive strength (\(f_{\text{cu}}\)) of alkali-activated concrete was measured at the ages of 1, 7, and 28 days according to BS EN 12390-3 \[74\]. The cylinder compressive strength (\(f'_{\text{c}}\)) was evaluated using 28-day cylinders (100 mm diameter × 200 mm height) per ASTM C39 \[75\].

The modulus of elasticity (\(E_c\)) of 28-day alkali-activated concrete was obtained according to ASTM C469 \[76\]. Four 60-mm-long strain gauges were installed at mid-height on diametrically opposite sides of the circumference of 100 mm diameter × 200 mm height cylinder to record the compression strain. A 500-kN compression load cell was also used to determine the compressive load which was applied at a loading rate of 7 kN/s. The load and strain were recorded using a data acquisition system. The modulus of elasticity was obtained as the slope of the chord connecting the stress corresponding to 40% of the ultimate stress (\(S_2\)) and that corresponding to a strain of 0.00005 (\(S_1\)). Equation (1) was employed in the calculation of the modulus of elasticity.

\[
E_c = \frac{S_2 - S_1}{\varepsilon_2 - 0.00005}
\]  

(1)

The tensile strength of 28-day alkali-activated slag-fly ash blended concrete mixtures was indirectly measured using the splitting tensile strength (\(f_{\text{sp}}\)) test of ASTM C496 \[77\]. Cylinders of 100 mm diameter and 200 mm height were used. The load was applied at a loading rate of 1 kN/s across the entire length of the specimen.

The water absorption of alkali-activated slag-fly ash blended concrete was evaluated as per the standard procedure of ASTM C642 \[78\]. The test was conducted on 28-day concrete disc specimens of 100 mm diameter and 50 mm height. The specimens were dried in an oven at 105 °C for 24 h until a mass change <0.5% was attained. The recorded mass was denoted as an “oven-dried mass”. The specimens were then immersed in water for
24 h, and the mass of the SSD sample was recorded as “SSD mass”. The water absorption was calculated using Equation (2).

\[
\text{Water absorption (\%) = } \frac{\text{SSD mass (g)} - \text{Oven-dried mass (g)}}{\text{Oven-dried mass (g)}} \times 100\%
\]  

(2)

The sorptivity is an indirect measure of the material’s short-term durability, as it relates to the tendency of a material to absorb and transmit water and other liquids by capillarity action. The sorptivity test was performed on 28-day concrete disc samples, similar to those used in the water absorption test, following the procedure of ASTM C1585 [79]. Prior to testing, samples were vacuum-saturated and preconditioned as per ASTM C1202 [80]. The rate of water absorption, i.e., sorptivity, was determined by measuring the increase in the mass of a sample as a function of time. In fact, the mass was recorded at 1, 5, 10, 15, 20, 30, and 60 min and then after every hour until 6 h. The absorption \(I\) was then calculated using Equation (3). Subsequently, the initial sorptivity \((\text{mm/s}^{1/2})\) was determined as the slope of the line of the best fit of absorption against the square root of time \((\text{s}^{1/2})\).

\[
\text{Absorption, } I \quad (\text{mm}) = \frac{\text{Change in mass at time } t \quad (\text{g})}{\text{Exposed area (mm}^2\text{)} \times \text{Density of water (g/mm}^3\text{)}} \times \text{Density of water (g/mm}^3\text{)}
\]

(3)

The general quality and integrity of the 28-day alkali-activated slag-fly ash blended concrete was evaluated using the direct ultrasonic pulse velocity (UPV) test. Indeed, the test indirectly estimated the content of voids, cracks, and imperfections. The procedure of ASTM C597 [81] was followed to determine the UPV of three 100-mm cube samples.

The resistivity of the concrete to the diffusion of chloride ions due to electrical current is represented by the bulk electric resistivity. A higher resistivity is indicative of higher protection against steel corrosion, as noted by ACI 222R-01 [82]. A 28-day concrete cylinder (100 mm diameter \times 200 mm height) was preconditioned according to ASTM C1202 [80] and saturated in preparation for testing as per ASTM C1876 [83]. Equation (4) was employed to determine the bulk resistivity in \(\Omega \cdot \text{cm}\). Yet, it should be noted that steel fiber-reinforced mixtures were not tested due to the conductive nature of the steel fibers, leading to nonrepresentative results.

\[
\text{Bulk Resistivity } (\Omega \cdot \text{cm}) = \frac{\text{Applied voltage (V) \times (Avg. sample diameter (mm))}^2}{1273.2 \times \text{Current at 1 min (mA) \times Avg. sample length (mm)}}
\]

(4)

To evaluate the alkali-activated slag-fly ash blended concrete resistance to abrasive, friction, and rubbing action, the abrasion resistance was determined. It is an indication of the probable future durability of the concrete incorporating different quantities of RCA and steel fibers [84,85]. For this test, a Los Angeles (LA) abrasion machine was utilized to measure the mass loss in 28-day concrete due to abrasive and impact forces in accordance with the procedure of ASTM C1747 [86]. The mass of disc specimens (50 mm height \times 100 mm diameter) was recorded before and after every 100 revolutions for a total of 500 revolutions. The abrasion resistance potential was determined as the percent mass loss of the sample as a function of the initial mass.

4. Results and Discussion

This section describes, discusses, and interprets the experimental test results for alkali-activated slag-fly ash blended concrete incorporating RCA and steel fibers. A comparative analysis highlighting the performance of concrete mixtures made with slag-to-fly ash ratios of 3:1 and 1:1 is also presented.

4.1. Compressive Strength

4.1.1. Strength Development Profile of Cubes

The cube compressive strength \(f_{cu}\) development profiles of alkali-activated slag concrete with 25% fly ash replacement and incorporating steel fibers and RCA are evaluated
The reported values represent the average of three specimens per mixture. The control mixture (S75R0F0) exhibited compressive strengths of 31.5, 44.2, and 56.8 MPa at the age of 1, 7, and 28 days, signifying increases of 40% and 29% from 1 to 7 days and 7 to 28 days, respectively. Also, 55% and 78% of the 28-day strength were attained at the ages of 1 and 7 days. This shows that the activation reaction was more significant within the first 7 days, owing to an accelerated reaction of slag and the production of calcium aluminosilicate hydrate and calcium-silicate-hydrate gels [87–90]. Temuujin, et al. [91] also concluded that the high molarity of the SH solution may improve the reaction efficiency at an early age. While significant strength had developed within the first 7 days, the increase up to 28 days is indicative of the continuous reaction of the fly ash to produce sodium aluminosilicate hydrate (N-A-S-H), as also reported by Ismail, et al. [92]. However, such an increase in strength was more pronounced with the replacement of NA by RCA, as per Table 5. In fact, 30%, 70%, and 100% RCA replacement in plain alkali-activated concrete led to respective 1 to 7 day increases of 59%, 77%, and 91%. Lower increases were noted from 7 to 28 days, as in the case of the control mixture. It seems that the RCA had a more significant impact at an early age of 1 day, owing to the weak bond between the blended binder matrix and RCA. Nevertheless, the addition of steel fibers reduced the 1 to 7 day strength gain. In fact, it was 75%, 61%, and 47%, on average, upon the incorporation of 0, 1%, and 2% steel fiber volume fractions, respectively. Meanwhile, the increase in strength from 7 to 28 days was 25%, 29%, and 30% for the same respective steel fiber volume fractions. Clearly, steel fiber inclusion improved the 1-day $f_{cu}$, leading to lower strength gains over time compared to the plain counterparts.

Table 5. Compressive strength of alkali-activated slag-fly ash concrete mixtures.

| Mix No. | Mix Designation | 1-Day ($f_{cu}$ (MPa)) | 7-Day ($f_{cu}$ (MPa)) | 28-Day ($f_{cu}$ (MPa)) | $f'_{c}$ (MPa) | Increase 1–7 (%) | Increase 7–28 (%) | $f'_{c}/f_{cu}$ |
|---------|-----------------|------------------------|------------------------|------------------------|----------------|----------------|----------------|----------------|
| 1       | S75R0F0         | 31.5                   | 44.2                   | 56.8                   | 31.5           | 40.3           | 28.5           | 0.55           |
| 2       | S75R30F0        | 26.3                   | 41.8                   | 52.6                   | 28.4           | 58.8           | 25.8           | 0.54           |
| 3       | S75R30F1        | 30.2                   | 42.7                   | 61.7                   | 38.3           | 41.4           | 44.5           | 0.62           |
| 4       | S75R30F2        | 33.8                   | 45.5                   | 63.8                   | 40.6           | 34.6           | 40.2           | 0.64           |
| 5       | S75R70F0        | 19.8                   | 35.0                   | 45.2                   | 18.4           | 76.8           | 29.1           | 0.41           |
| 6       | S75R70F1        | 24.0                   | 40.1                   | 49.1                   | 28.4           | 67.1           | 22.4           | 0.58           |
| 7       | S75R70F2        | 30.6                   | 44.3                   | 55.8                   | 33.0           | 44.8           | 26.0           | 0.59           |
| 8       | S75R100F0       | 18.4                   | 35.1                   | 42.5                   | 15.7           | 90.8           | 21.1           | 0.37           |
| 9       | S75R100F1       | 22.6                   | 39.7                   | 48.0                   | 26.5           | 75.7           | 20.9           | 0.55           |
| 10      | S75R100F2       | 25.8                   | 41.7                   | 51.4                   | 31.7           | 61.6           | 23.3           | 0.62           |
| 11      | S50R0F0         | 9.1                    | 28.6                   | 35.3                   | 29.7           | 215.8          | 23.1           | 0.84           |
| 12      | S50R30F0        | 9.8                    | 30.6                   | 31.0                   | 17.4           | 191.3          | 8.5            | 0.56           |
| 13      | S50R30F1        | 11.4                   | 34.6                   | 37.7                   | 34.1           | 198.5          | 12.5           | 0.79           |
| 14      | S50R30F2        | 12.9                   | 38.5                   | 43.4                   | 31.1           | 203.0          | 9.1            | 0.82           |
| 15      | S50R70F0        | 5.7                    | 25.2                   | 28.2                   | 11.6           | 342.7          | 12.1           | 0.41           |
| 16      | S50R70F1        | 10.4                   | 27.4                   | 34.7                   | 19.5           | 163.7          | 18.4           | 0.56           |
| 17      | S50R70F2        | 15.3                   | 35.8                   | 36.8                   | 31.9           | 134.6          | 2.8            | 0.87           |
| 18      | S50R100F0       | 12.5                   | 24.4                   | 28.1                   | 10.4           | 95.2           | 15.3           | 0.39           |
| 19      | S50R100F1       | 13.7                   | 28.1                   | 33.2                   | 18.9           | 104.4          | 18.3           | 0.57           |
| 20      | S50R100F2       | 12.7                   | 27.9                   | 34.7                   | 28.3           | 120.6          | 24.3           | 0.82           |

* Increase in $f_{cu}$ from 1 to 7 days. b Increase in $f_{cu}$ from 7 to 28 days.

Furthermore, the strength development profile of alkali-activated concrete made with equal proportions of slag and fly ash was examined in Table 5. The compressive strength of the control mixture (S50R0SF0) at 1, 7, and 28 days was 9.1, 28.6, and 35.3 MPa, respectively, representing corresponding increases of 214% and 23% from 1 to 7 days and 7 to 28 days. Such poor early-age performance was due to the curing of alkali-activated mixtures made with high fly ash content at ambient conditions, as reported in other work [25,86]. Similar strength increase trends were noted for other mixtures irrespective of RCA replacement percentage and steel fiber volume fraction. Yet, it is worth noting that the increase in
strength over time generally decreased as more steel fiber was added to the concrete mixture. In fact, $f_{cu}$ increased by 210%, 157%, and 151%, on average, from 1 to 7 days for mixtures made with 0, 1%, and 2% steel fiber, by volume.

4.1.2. Effect of RCA Replacement

Figures 5–7 present the 1-, 7-, and 28-day compressive strengths of alkali-activated slag-fly ash blended concrete while highlighting the RCA replacement percentage and steel fiber volume fraction. For mixtures made with a slag-to-fly ash ratio of 3:1, the replacement of NA by RCA had an adverse effect on $f_{cu}$. In fact, RCA replacement of 30%, 70%, and 100% decreased the 1-day strength by 16%, 37%, and 42%, respectively, compared to the NA-based control (S75R0F0), as depicted in Figure 5a. Conversely, the 7-day strength [Figure 6a] was reduced by 5%, 21%, and 21%, and the 28-day strength [Figure 7a] was lower by 7%, 20%, and 25%. This reduction in strength could be associated with the weak interfacial bond between the aggregate and alkali-activated matrix as well as the rough porous nature of the RCA [93]. Analogous findings were reported in other work on alkali-activated fly ash and slag mortars and concrete incorporating recycled aggregates [28,40–47]. Yet, this negative impact of RCA was less pronounced at a later age, possibly due to a stronger matrix attributed to the late reaction of fly ash, as reported in the literature [94].

**Figure 5.** Cubic compressive strength of 1-day alkali-activated slag-fly ash blended concrete mixtures: (a) 3:1 slag:fly ash; (b) 1:1 slag:fly ash.

**Figure 6.** Cubic compressive strength of 7-day alkali-activated slag-fly ash blended concrete mixtures: (a) 3:1 slag:fly ash; (b) 1:1 slag:fly ash.

The effect of RCA replacement percentage on $f_{cu}$ of alkali-activated concrete incorporating equal proportions of slag and fly ash is shown in Figures 5b, 6b and 7b. Generally, the replacement of NA by RCA did not have a significant impact on the 1-day strength, owing to a possibly sufficient interfacial bond between the alkali-activated binder and coarse aggregates (NA and RCA). Figure 6b presents the 7-day cube compressive strength. While the replacement of NA by 30% RCA did not have a substantial effect on the 7-day strength, higher replacements of 70% and 100% reduced the strength by 12% and 15%, respectively.
respectively. Furthermore, the 28-day \( f_{cu} \) values ranged between 28.1 and 43.4 MPa, as shown in Figure 7b. While the control mixture with 100% NA had a 28-day \( f_{cu} \) of 35.3 MPa, those of mixtures that replaced NA by 30%, 70%, and 100% RCA were 31.0, 28.2, and 28.1 MPa, representing decreases of 12%, 20%, and 20%, respectively. Similar findings were reported in alkali-activated concrete made with a single precursor, i.e., class C fly ash, class F fly ash, or slag [42,44,95].

Figure 7. Cubic compressive strength of 28-day alkali-activated slag-fly ash blended concrete mixtures: (a) 3:1 slag:fly ash; (b) 1:1 slag:fly ash.

4.1.3. Effect of Steel Fiber Addition

The influence of adding steel fibers on \( f_{cu} \) of alkali-activated slag concrete made with 25% fly ash is examined in Figures 5a, 6a and 7a. Compared to the plain counterparts, the 1-, 7-, and 28-day strength increased, on average, by 20%, 10%, and 13% upon adding 1% steel fibers, by volume, respectively, and by 41%, 18%, and 22% with 2% steel fiber volume fraction, respectively. Clearly, steel fibers countered the negative effect of RCA replacement, especially at higher volume fractions due to the bridging effect of steel fibers, increase in density of the matrix, and reduction in the pore space, evidenced by the lower water absorption and sorptivity results shown later. Yet, the improvement in \( f_{cu} \) seemed to be superior at the age of 1 day. Similar enhancements in compressive strength were noted in steel fiber-reinforced alkali-activated concrete made with NA [36,96]. Indeed, it is possible to produce alkali-activated slag-fly ash (3:1) concrete incorporating dune sand with up to 30% RCA replacement without steel fibers and up to 100% RCA with 2% steel fibers, by volume, while sustaining a limited loss (<10%) in the 28-day cube compressive strength.

Figures 5b, 6b and 7b present the effect of steel fiber inclusion on \( f_{cu} \) of alkali-activated concrete made with equal proportions of slag and fly ash. Results highlight respective increases of, on average, 36, 12, and 11, in 1-, 7-, and 28-day \( f_{cu} \) when 1% steel fibers, by volume, were incorporated into the plain alkali-activated concrete mixtures. Upon the inclusion of 2% steel fibers, by volume, \( f_{cu} \) improved by, on average, 67%, 24%, and 28%, respectively. As a result, it could be concluded that the full replacement of NA by RCA (100%) is possible in alkali-activated slag-fly ash (1:1) concrete incorporating at least 1% steel fibers, by volume, while sustaining a limited loss (<6%) in the 28-day compressive strength.

4.1.4. Cylinder Compressive Strength

The effect of RCA replacement and steel fiber incorporation on the 28-day cylinder compressive strength (\( f'_c \)) of alkali-activated slag concrete with 25% fly ash replacement is presented in Table 5. It can be clearly seen that the replacement of NA by RCA resulted in a decrease in \( f'_c \). Indeed, 30%, 70%, and 100% RCA replacement led to a reduction of 10%, 42%, and 50% in \( f'_c \), respectively. These values are much higher than those reported for cube compressive strength, especially for 70% and 100% RCA replacement, signifying a possible compounded effect of specimen geometry and RCA replacement. Nevertheless, the addition of 1 and 2% steel fibers volume fractions enhanced \( f'_c \) by up to 69% and 101%, respectively. As such, alkali-activated slag concrete mixtures blended with 25% fly ash and
incorporating dune sand can be produced with up to 30% RCA without steel fibers and up to 100% RCA with 2% steel fibers, by volume, while accepting a limited loss (<10%) in \( f'_{c} \).

Table 5 also shows the values of \( f'_{c} \) of alkali-activated concrete with equal proportions of slag and fly ash. Similar to the 28-day cube compressive strength results, increasing the RCA replacement percentage led to a decrease in the 28-day cylinder compressive strength. In fact, 30%, 70%, and 100% RCA replacement resulted in 26%, 51%, and 54% respective reductions in strength. This is possibly owed to the old, adhered mortar surrounding the RCA that created a weak interfacial zone with the geopolymeric paste. It is also likely due to the poor quality and abundance of cracks and voids of the RCA [97]. Also, the RCA-associated loss in strength was more pronounced in the cylinder samples rather than the cube counterparts. Furthermore, the addition of 1% and 2% steel fibers, by volume, enhanced the strength of the RCA plain concrete by up to 79% and 174%, respectively. Accordingly, it is possible to produce alkali-activated concrete made with dune sand, equal proportions of slag and fly ash, and up to 30% RCA with 1% steel fiber, by volume. Mixtures with RCA replacements up to 100% can be also produced in conjunction with 2% steel fibers, by volume, with less than 5% loss in \( f'_{c} \). A comparison with results of an investigation on cement-based conventional concrete mixtures shows that less steel fiber volume fractions are needed in the case of using alkali-activated slag-fly ash blended binder, rendering this binder more suitable for concrete made with more than 30% RCA, by mass [53].

4.1.5. Variability in the Results

For mixtures made with slag-to-fly ash ratio of 3:1, the variability in \( f_{cu} \) and \( f'_{c} \) results increased with higher RCA replacement percentages. In fact, the coefficients of variation of \( f_{cu} \) at 1, 7, and 28 days of age and \( f'_{c} \) increased from 5.6% to 11.3%, 5.5% to 6.4%, 3.2% to 6.6%, and 4.8% to 8.3%, respectively, as more NA was replaced by RCA. Moreover, the variability of \( f_{cu} \) and \( f'_{c} \) results for mixtures made with equal proportions of slag and fly ash was insignificantly affected by the replacement of NA by RCA, where the coefficients of variation of the 1-, 7-, and 28-day \( f_{cu} \) and \( f'_{c} \) were in the respective ranges of 9.0–10.0%, 7.4–7.9%, 2.7–3.7%, and 4.8–5.4%. Meanwhile, the addition of steel fibers to both types of alkali-activated concrete had no noticeable impact on the variability of the results despite their apparent improvement in performance.

4.1.6. Cylinder-to-Cube Compressive Strength Ratio

The \( f'_{c}/f_{cu} \) ratio of alkali-activated slag-fly ash (3:1) blended concrete is shown in Table 5. For the control mixture (S75R0F0), the ratio was 0.55. Yet, this value decreased to 0.54, 0.41, and 0.37 as RCA replacement increased to 30%, 70%, and 100%. This shows that the effect of RCA was more pronounced in the cylinder samples, signifying a more critical impact of RCA replacement for samples with a higher aspect ratio. Moreover, the addition of 1% and 2% steel fibers, by volume, increased the \( f'_{c}/f_{cu} \) ratio to up to 0.62 and 0.64, respectively. These results are slightly lower than those of conventional cement-based concrete with a typical \( f'_{c}/f_{cu} \) ratio ranging between 0.65 and 0.90 [98]. A possible relationship between \( f'_{c} \) and \( f_{cu} \) is shown in Figure 8 and Equations (5) and (6). With these analytical relations, it is possible to predict one property from the other with moderate \( R^2 = 0.70 \) and high accuracy \( R^2 = 0.91 \) rather than conducting two separate experimental tests according to ASTM C39 [75] and BS EN 12390-3 [74]. The equations could be employed for the range of compressive strength values presented in this work.

\[
\frac{f'_{c}}{f_{cu}} = 0.56f_{cu} \tag{5}
\]

\[
\frac{f'_{c}}{f_{cu}} = 1.08f_{cu} - 27.54 \tag{6}
\]

The \( f'_{c}/f_{cu} \) ratio of alkali-activated concrete made with equal proportions of slag and fly ash is shown in Table 5. The ratio of the control mixture made with 100% NA and no steel fiber was 0.84. It decreased as more NA was replaced by RCA in plain concrete. This
signifies that the difference between cube and cylinder compressive strength increased as more RCA was incorporated into the concrete mixture. Yet, this ratio was higher as more steel fiber was added to the mixture. In fact, it increased, on average, to 0.69 and 0.80 with 1% and 2% steel fiber volume fractions. Based on these results, it is apparent that a relationship exists between the cylinder and cube compressive strengths at the age of 28 days, as illustrated in Figure 8. The relationships, shown in Equations (7) and (8), indicate the ability to predict \( f_c' \) from \( f_{cu} \) (or vice versa) for the values shown herein with moderate to reasonable accuracy (\( R^2 = 0.57 \) and 0.90, respectively).

\[
f_c' = 0.69f_{cu} \tag{7}
\]

\[
f_c' = 1.70f_{cu} - 35.09 \tag{8}
\]

Figure 8. Relationship between cubic and cylinder compressive strength.

To estimate \( f_c' \) from \( f_{cu} \) or vice versa, past literature developed equations for conventional cement-based concrete made with steel fibers and RCA [52,53,99,100]. The ability to utilize these equations for alkali-activated slag-fly ash blended concrete is examined in Figure 9. As shown in Figure 9a, all literature equations overestimate \( f_c' \) of mixtures made with 25% fly ash, while Equations (5) and (6) provide the highest accuracy. Conversely, equations proposed by [52,53,99,100] could accurately predict \( f_c' \) of mixtures with equal proportions of slag and fly ash for values in the vicinity of 30 MPa, but overestimated \( f_c' \) for lower values [Figure 9b]. In turn, Equations (7) and (8) were most accurate in predicting \( f_c' \).

Figure 9. Predicted versus experimental cylinder compressive strength for mixtures with slag-fly ash of: (a) 3:1; (b) 1:1.
4.2. Compressive Stress-Strain Response

4.2.1. Effect of RCA Replacement

The influence of RCA replacement on the compression behavior of alkali-activated slag-fly ash (3:1) concrete mixtures is highlighted in Figure 10. The stress-strain response of the NA-based control mixture is also presented and serves as a benchmark. RCA replacement percentages of 30%, 70%, and 100% in plain concrete led to decreases of 15%, 41%, and 50% in the peak stress, respectively, compared to the NA-based control mixture. This is primarily due to the weak and porous nature of RCA and lower concrete elastic modulus. Other work on conventional cement-based concrete reported analogous findings [44,50,89,91–93]. Furthermore, less pronounced reductions in peak stress were reported when RCA replaced NA in steel fiber-reinforced mixtures. In fact, every 10% RCA replacement in mixtures incorporating 0%, 1%, and 2% steel fiber volume fractions reduced the peak stress by 5.3%, 3.9%, and 3.2%, respectively. For the same mixtures, the peak strain increased by 0.4%, 1.4%, and 3.2%, respectively. As RCA replacement increases, the strength of the concrete decreases, causing higher strain at peak load.

![Figure 10. Typical compression stress-strain curves of RCA alkali-activated slag-fly ash (3:1) concrete mixtures with RCA replacement of (a) 30%, (b) 70%, and (c) 100%.

Figure 10 presents the compressive stress-strain behavior of alkali-activated concrete made with a slag-to-fly ash ratio of 1:1. Mixtures with different RCA replacement and steel fiber volume fractions are plotted alongside the NA-based control. The increase in RCA replacement led to a decrease in peak stress regardless of the steel fiber volume fraction. In fact, mixtures made with 0%, 1%, and 2% steel fiber, by volume, experienced 7.0%, 5.2%, and 2.5% respective reductions in peak stress with every 10% NA replaced by RCA. Furthermore, the peak strain generally increased as more RCA was incorporated into the mixture. Indeed, a similar analysis showed the peak strain increased by 4.5%, 2.5%, and 2.2%, respectively.

![Figure 11. Typical compression stress-strain curves of RCA alkali-activated slag-fly ash (1:1) concrete mixtures with RCA replacement of (a) 30%, (b) 70%, and (c) 100%.

Figure 11 presents the compressive stress-strain behavior of alkali-activated concrete made with a slag-to-fly ash ratio of 1:1. Mixtures with different RCA replacement and steel fiber volume fractions are plotted alongside the NA-based control. The increase in RCA replacement led to a decrease in peak stress regardless of the steel fiber volume fraction. In fact, mixtures made with 0%, 1%, and 2% steel fiber, by volume, experienced 7.0%, 5.2%, and 2.5% respective reductions in peak stress with every 10% NA replaced by RCA. Furthermore, the peak strain generally increased as more RCA was incorporated into the mixture. Indeed, a similar analysis showed the peak strain increased by 4.5%, 2.5%, and 2.2%, respectively.
4.2.2. Effect of Steel Fiber Addition

Figure 10 shows that, for every 1% increase in steel fibers, by volume, the peak stress of alkali-activated slag-fly ash (3:1) blended concrete mixtures made with 30%, 70%, and 100% RCA increased by, on average, 14%, 24%, and 21%, respectively, while the corresponding peak strains increased by 16%, 26%, and 37%. Based on these results, it is clear that the incorporation of steel fibers increased the deformability of concrete made with RCA while also enhancing the compressive stress. Yet, it is worth noting that, despite the fact that steel fibers resulted in concrete with similar peak strains, the tail part of the compressive stress-strain curve was longer with higher steel fiber volume fractions, highlighting the enhanced energy absorption capacity.

The effect of different steel fiber volume fractions on the compressive stress-strain behavior of alkali-activated concrete with equal proportions of slag and fly ash is examined in Figure 11. The peak stress increased by an average of 91%, 73%, and 72% for every 1% steel fiber volume fraction added to the concrete mixture incorporating 30%, 70%, and 100% RCA, respectively, while the peak strain increased by 132%, 75%, and 113%, respectively. A comparison with conventional cement-based concrete with a similar design compressive strength of 30 MPa shows that alkali-activated slag-fly ash blended binders experienced higher increases in peak stress and strain [53].

4.3. Modulus of Elasticity

4.3.1. Effect of RCA Replacement

The modulus of elasticity, $E_c$ (in GPa), refers to the ability of a material to endure sustained stress as the strain increases within the elastic limit. It was determined by analyzing the stress-strain curves in accordance with ASTM C469 [76]. Figure 12 shows the $E_c$ of 28-day alkali-activated slag-fly ash (3:1) blended concrete with different RCA replacement and steel fiber volume fractions. Decreases of 28%, 43%, and 52% in $E_c$ were noted when NA was replaced by 30%, 70%, and 100% RCA, respectively.

![Figure 12](image-url)

Figure 12. Modulus of elasticity of alkali-activated slag concrete mixtures with different RCA replacement percentages and SF volume fractions.

Figure 12 also illustrates the modulus of elasticity of 28-day alkali-activated concrete made with equal portions of slag and fly ash. An increase in RCA replacement percentage led to a decrease in $E_c$. In fact, 30%, 70%, and 100% RCA replacement in plain concrete decreased $E_c$ by 17%, 36%, and 63%, respectively. The reductions in $E_c$ for both types of mixtures (slag-to-fly ash of 3:1 and 1:1) could be attributed to the weak and porous structure of RCA, porous old, adhered mortars, microcracks in the RCA, and weak interfacial bond between the old mortar and aggregate. Other work reported similar RCA-induced reductions in $E_c$ of geopolymer concrete [26,45,47,72].
4.3.2. Effect of Steel Fiber Addition

Experimental test results showed that $E_c$ increased by, on average, 38%, 28%, and 44% for every 1% steel fiber, by volume, added to 30%, 70%, and 100% RCA concrete. Such increases in $E_c$ are owed to the ability of steel fibers to densify the alkali-activated binder matrix and decrease the pore space, evidenced by the water absorption results shown later, and their bridging effect, which mitigates the initiation and propagation of microcracks. Accordingly, alkali-activated slag-fly ash (3:1) concrete mixtures made with RCA and steel fibers were between 53% lower and 18% higher than that of the control mixture S75R0F0, signifying that steel fibers cannot only reverse the negative impact of RCA but could also enhance the modulus of elasticity to the extent of exceeding that of the control mixture for some mixtures.

For mixtures made with equal portions of slag and fly ash, $E_c$ increased with steel fiber addition. For 30%, 70%, and 100% RCA replacement, the addition of 1% steel fiber, by volume, to plain counterparts increased $E_c$ by 12%, 3%, and 23%, respectively, while 2% steel fiber volume fraction led to respective increases of 17%, 12%, and 41%. Based on these results, it can be concluded that the effect of RCA replacement on $E_c$ of alkali-activated slag-fly ash (1:1) blended concrete was more prominent than the addition of steel fibers. As such, the majority of RCA-based mixtures experienced lower $E_c$ than the control (S50R0F0).

4.3.3. Variability in the Results

The coefficient of variation of the modulus of elasticity for mixtures made with slag-to-fly ash ratio of 3:1 increased from 7.4% to 10.3% as more NA was replaced by RCA. On the other hand, mixtures having equal portions of slag and fly ash reported minor increases in variability of $E_c$ with coefficient of variation values ranging between 7.7% and 9.2%. This shows that increasing the RCA replacement led to slightly higher variability in the $E_c$ results, owing to the inert variability in the nature of the RCA. Contrarily, both types of alkali-activated concrete did not experience a notable change in the variability of the results upon the inclusion of steel fibers.

4.3.4. Analytical Correlations

The modulus of elasticity results showed herein were correlated to the 28-day cylinder compressive strength. For alkali-activated slag concrete mixtures incorporating 25% fly ash, the developed analytical relationship is in the form of Equation (9) and is shown in Figure 13. It is clear that a moderate correlation ($R^2 = 0.72$) exists between the two mechanical properties. This is due to the significant impacts of RCA replacement and steel fiber inclusion on $E_c$. Accordingly, a regression model involving these two elements and $f'_c$ was developed. Equation (10) presents this relationship, where $f'_c$ is the 28-day cylinder compressive strength in MPa, RCA is the RCA replacement percentage, and SF is the steel fiber volume fraction. With an $R^2$ value of 0.91, this equation can be used to accurately predict $E_c$ for the range of values depicted in this work. From the coefficients of Equation (10), it is clear that $E_c, f'_c$, and steel fiber volume fraction share a proportional relationship, signifying that an increase in $f'_c$ and inclusion of steel fibers lead to higher $E_c$ values. In contrast, $E_c$ and RCA replacement percentage are inversely proportional, indicating that RCA has a negative impact on $E_c$.

A similar analysis was carried out for alkali-activated concrete made with equal portions of slag and fly ash. The first analytical model [Equation (11)] developed using the scatter plot of Figure 13 showed a moderate correlation ($R^2 = 0.47$) between $E_c$ and $f'_c$. Accordingly, the RCA replacement was incorporated into the model to formulate Equation (12) and accurately predict $E_c$ with $R^2 = 0.91$ for values of $f'_c$ and RCA illustrated herein. Upon the inclusion of steel fiber volume fraction, its coefficient was negligible. As such, it was omitted from the equation. Furthermore, the coefficients indicate a positive impact of $f'_c$ and a negative impact of RCA on $E_c$.

$$E_c = 3.44 \sqrt{f'_c}$$  \hspace{1cm} (9)
The feasibility of employing equations developed by codes and past literature was examined. Figure 14a plots the experimental and predicted modulus of elasticity of alkali-activated slag-fly ash (3:1) blended concrete. Equation (10) developed herein was compared to codified equations of ACI Committee 318 [101], CEB-FIP [102], AS3600 [103], and other relevant equations proposed in the literature [35,36,94]. With values mainly converging around the 45°-line, it is clear that Equation (10) and the equation proposed by El-Hassan, Shehab, and Al-Sallamin [94] provided the most accurate predictions. Conversely, the equation of AS3600 [103] provides predictions with acceptable accuracy for $E_c$ between 15 and 20 GPa but deviates from the experimental result for $E_c$ outside this range. Indeed, the error between the experimental and predicted $E_c$ was in the range of 3% to 30%. Conversely, the error associated with utilizing the equations of ACI Committee 318 [101], CEB-FIP [102], and El-Hassan and Elkholy [36] reached up to 133%. Accordingly, some modifications to the codified equations are needed to accurately predict the $E_c$ of alkali-activated slag-fly ash (3:1) blended concrete. In turn, few equations from the literature may be suitable for predicting $E_c$ from $f'_c$ with reasonable accuracy.

$$E_c = 3.78 \sqrt{f'_c} - 0.05RCA + 1.16SF$$
(10)

$$E_c = 1.91 \sqrt{f'_c}$$
(11)

$$E_c = 0.091f'_c - 0.065RCA + 10.845$$
(12)

The obtained relationship in Equation (12) for alkali-activated concrete made with equal portions of slag and fly ash was compared to those developed by ACI Committee 318 [101], CEB-FIP [102], AS3600 [103], and other researchers [35,36,94]. Figure 14b depicts the predicted values of $E_c$ versus the experimental ones. With scatter plots converging...
around the 45°-line, it can be noted that the model presented herein as Equation (12) was more accurate at predicting the values of \( E_c \). While the equations suggested by ACI Committee 318 [101], CEB-FIP [102], and other authors [36,94] significantly overestimated \( E_c \), the models proposed by AS3600 [103] and El-Hassan, Shehab, and Al-Sallamin [35] provided moderate prediction accuracy. As such, the codified equations and those developed in past work are deemed unsuitable for the alkali-activated concrete produced in this work and require certain modifications to account for the RCA replacement and steel fiber incorporation.

### 4.4. Splitting Tensile Strength

#### 4.4.1. Effect of RCA Replacement

Figure 15 illustrates the effect of RCA replacement and steel fiber incorporation on the 28-day splitting tensile strength of alkali-activated slag-fly ash (3:1) blended concrete. The replacement of NA by 30%, 70%, and 100% RCA resulted in 13%, 31%, and 35% respective losses in \( f_{sp} \). These losses were generally lower than those noted in \( f'_{c} \) (15%, 41%, and 50%). As such, it should be noted that the negative impact of RCA replacement was generally more pronounced on \( f'_{c} \) than on \( f_{sp} \).

The values of \( f_{sp} \) of 28-day alkali-activated concrete made with equal portions of slag and fly ash are also presented in Figure 15. The results show that \( f_{sp} \) was reduced by 17%, 37%, and 47%, when 30%, 70%, and 100% RCA replaced NA, respectively. Other authors reported a similar adverse effect of RCA on the \( f_{sp} \) of geopolymer concrete made with fly ash or a blend of fly ash and slag [45,47]. In comparison, \( f'_{c} \) decreased by 26, 51, and 54 for the same RCA replacement percentages. This indicates that RCA replacement was more influential on \( f'_{c} \) than on \( f_{sp} \).

#### 4.4.2. Effect of Steel Fiber Addition

The adverse effect of RCA was reversed by the addition of steel fibers. In fact, mixtures made with a slag-to-fly ash ratio of 3:1 and incorporating 1% and 2% steel fibers, by volume, displayed increases in \( f_{sp} \) by 87% and 194%, respectively, with values up to 7.7 MPa. Similar findings were noted in past research that examined the \( f_{sp} \) of NA-based alkali-activated concrete incorporating steel fibers [36,95,104]. Such enhancement surpasses that experienced by \( f'_{c} \), signifying that the more prominent impact of steel fiber addition on \( f_{sp} \) rather than \( f'_{c} \). Accordingly, it can be concluded that alkali-activated slag concrete 25% fly ash replacement can be produced with up to 100% RCA and in conjunction with 1% steel fiber volume fraction with superior performance to that of the plain NA-based control (S75R0F0).

The effect of adding steel fibers on \( f_{sp} \) of alkali-activated concrete made with equal portions of slag and fly ash was also investigated. The addition of 1% and 2% steel fiber, by volume, increased \( f_{sp} \) by, on average, 134% and 230%, respectively, compared to the plain concrete counterparts. In fact, \( f_{sp} \) could reach up to 4.4 and 4.9 MPa compared to 2.2 MPa.
for the control mixture (S50R0F0). It is clear that the adverse impact of NA replacement by RCA on $f_{sp}$ could not only be reversed by steel fiber addition but could also exceed that of the control. This is primarily owed to the steel fibers’ ability to bridge the microcracks and increase the energy requirements for crack propagation. As such, alkali-activated concrete made with equal portions of slag and fly ash and 100% RCA can be produced with superior performance to that of the control mixture (S50R0F0) subject where 1% steel fiber, by volume, is incorporated in the mixture.

4.4.3. Variability in the Results

As RCA replaced NA in mixtures made with slag-to-fly ash ratios of 3:1 and 1:1, the coefficients of variation of $f_{sp}$ increased from 4.1% to 12.0% and from 5.0% to 12.1%, respectively. This shows that RCA replacement increased the variability in the $f_{sp}$ results, owing to the variations in the RCA and the virgin concrete. On the other hand, respective steel fiber-reinforced alkali-activated concrete mixtures exhibited slight changes in the coefficients of variation of $f_{sp}$ with respective values in the ranges of 6.6–8.2% and 6.8–8.7%. Generally, steel fiber incorporation did not enhance the variability in the $f_{sp}$ results of mixtures with 30% and 70% RCA replacement, whereas it reduced the variability of mixtures with 100% RCA replacement.

4.4.4. Analytical Correlations

The splitting tensile strength of concrete is usually predicted through codified equations that relate it to the 28-day cylinder compressive strength. Equation (13) and Figure 16 show the relationship between $f_{sp}$ and $f'_c$. With a low $R^2$ value of 0.41, the prediction capability of Equation (13) is limited. As such, Equation (14) was developed using multivariable linear regression analysis to predict $f_{sp}$ from $f'_c$, RCA replacement percentage, and steel fiber volume fraction for the range of values presented herein. The accuracy significantly increased with $R^2$ reaching 0.95.

$$f_{sp} = 0.80 \sqrt{f'_c}$$

(13)

$$f_{sp} = 0.56 \sqrt{f'_c} - 0.01 \text{RCA} + 1.83 \text{SF}$$

(14)


\[ f_{sp} = 0.68 \sqrt{f'_c} \]  
\[ f_{sp} = 0.44 \sqrt{f'_c} - 0.004\text{RCA} + 1.23\text{SF} \]

The employability of codified equations of ACI Committee 318 [101], CEB-FIP [102], AS3600 [103] to predict \( f_{sp} \) was assessed. The experimental splitting tensile strength was plotted against that predicted from the codified equations as well as Equations (14) and (16) for both types of alkali-activated concrete mixtures. Figure 17 shows that the codified models could predict \( f_{sp} \) with reasonable accuracy until a value of 3 MPa, after which these codes underestimated it. With unconventional alkali-activated slag-fly ash blended concrete made with RCA and steel fibers, codified equations cannot be employed for the prediction of \( f_{sp} \), because they do not account for the impact of RCA and steel fibers on \( f_{sp} \). In turn, Equations (14) and (16) provided accurate estimations of \( f_{sp} \).

4.5. Water Absorption

The durability of concrete can be evaluated by the rate at which harmful agents penetrate the concrete. In fact, concrete undergoes deterioration and damage due to the ingress of moisture or other aggressive liquids through the interconnected pores. As water is the primary carrier of aggressive ions, the ability of concrete to absorb water, characterized by its water absorption, can give a good indication of its durability [83]. Table 6 presents the water absorption of 28-day alkali-activated slag-fly ash blended concrete. For mixtures made with a slag-to-fly ash ratio of 3:1, the control mixture (S75R0F0) had a water absorption of 3.3%. Conversely, plain concrete made with 30%, 70%, and 100% RCA had water absorption of 3.7%, 4.8%, and 5.6%, respectively, representing 12%, 45%, and 70% respective increases. This shows that the water absorption increased by an average of 6% for every 10% NA replaced by RCA due to the porous adhered mortar and RCA. With the increase in water absorption, the mechanical properties decreased, including \( f'_c, f_{cu}, E_c \), and \( f_{sp} \). Additionally, the effect of incorporating steel fibers on alkali-activated slag-fly ash (3:1) blended concrete is examined in Table 6. An increase in steel fiber volume fraction led to a reduction in water absorption. Indeed, the addition of 1% and 2% steel fiber, by volume, decreased the water absorption by, on average, 12% and 17%, respectively, in comparison to the corresponding plain concrete mixtures. In conclusion, RCA replacement had a negative impact on the water absorption of alkali-activated slag-fly ash (3:1) blended concrete. Yet, it could be somewhat countered through the addition of steel fibers.

Table 6 also summarizes the water absorption test results of alkali-activated concrete made with equal portions of slag and fly ash at the age of 28 days. While the control specimen (S50R0SF0) had the lowest water absorption of 3.8%, mixtures made with 30%, 70%, and 100% RCA had values of 5.0%, 6.6%, and 6.8%, respectively. This represents 31%,
It can therefore be noted that the water absorption increased by 10%, on average, for every 10% NA replaced by RCA, owing to the porous structure of the adhered mortar to the RCA and additional void sites in the RCA. In addition, Table 6 shows that the water absorption decreased as steel fibers were incorporated into the mixture. The addition of 1% and 2% steel fiber volume fractions compared to plain concrete mixtures resulted in average reductions in water absorption of 12% and 20%, respectively. Clearly, the incorporation of steel fibers into alkali-activated slag-fly ash blended concrete made with RCA densified the matrix, leading to a decrease in the water absorption and an increase in mechanical performance. Bernal, De Gutierrez, Delvasto, and Rodriguez [104] reported similar findings for alkali-activated slag concrete made with NA and steel fibers.

Table 6. Water absorption and sorptivity of alkali-activated slag-fly ash blended concrete mixtures.

| Mix No. | Mix Designation | RCA (%) | Steel Fibers (%) | Water Absorption (%) | Sorptivity $\times 10^{-2}$ (mm/$\sqrt{s}$) |
|---------|-----------------|---------|------------------|----------------------|------------------------------------------|
| 1       | S75R0F0         | 0       | 0                | 3.3                  | 1.58                                     |
| 2       | S75R30F0        | 30      | 0                | 3.7                  | 2.17                                     |
| 3       | S75R30F1        | 30      | 1                | 2.9                  | 1.99                                     |
| 4       | S75R30F2        | 30      | 2                | 2.6                  | 1.83                                     |
| 5       | S75R70F0        | 70      | 0                | 4.8                  | 2.91                                     |
| 6       | S75R70F1        | 70      | 1                | 4.4                  | 2.78                                     |
| 7       | S75R70F2        | 70      | 2                | 4.2                  | 2.48                                     |
| 8       | S75R100F0       | 100     | 0                | 5.6                  | 3.58                                     |
| 9       | S75R100F1       | 100     | 1                | 5.3                  | 3.49                                     |
| 10      | S75R100F2       | 100     | 2                | 5.1                  | 3.21                                     |
| 11      | S50R0F0         | 0       | 0                | 3.8                  | 2.50                                     |
| 12      | S50R30F0        | 30      | 0                | 5.0                  | 3.51                                     |
| 13      | S50R30F1        | 30      | 1                | 4.4                  | 3.41                                     |
| 14      | S50R30F2        | 30      | 2                | 4.0                  | 3.32                                     |
| 15      | S50R70F0        | 70      | 0                | 6.6                  | 4.50                                     |
| 16      | S50R70F1        | 70      | 1                | 5.8                  | 4.31                                     |
| 17      | S50R70F2        | 70      | 2                | 5.2                  | 3.84                                     |
| 18      | S50R100F0       | 100     | 0                | 6.8                  | 5.96                                     |
| 19      | S50R100F1       | 100     | 1                | 6.0                  | 5.48                                     |
| 20      | S50R100F2       | 100     | 2                | 5.5                  | 4.75                                     |

4.6. Capillary Sorptivity

Sorptivity is a commonly used test to indirectly assess the durability of concrete, as it relates to the tendency of concrete to absorb and transport water by capillary action through its microstructure. In fact, the rate of absorption, i.e., sorptivity, of water depends on the strength of capillary forces, the permeability of the concrete, the porosity of the concrete, and the structure and distribution of the pores [83,105]. Sorptivity is categorized into two types: initial and secondary. The initial and secondary sorptivity are governed by the respective sorption processes through the large capillary and small gel pores [106]. Because water occupies the former pores faster than the latter ones, the initial sorptivity is typically higher than the secondary sorptivity. Accordingly, this work only focused on the initial sorptivity.

Figure 18a shows the typical absorption of plain alkali-activated slag-fly ash (3:1) blended concrete as a function of time. Mixtures made with 0, 30%, 70%, and 100% maintained the same initial slope up to 33, 60, 135, and 240 min (44, 60, 90, and 120 $s^{0.5}$), respectively, after which the slope decreased. This shows that the higher RCA replacement required more time to reach absorption stability due to the presence of voids in RCA. Higher RCA content also resulted in higher absorption at 360 min (147 $s^{0.5}$). Furthermore, 1% steel fiber volume fraction did not have a major impact on the slope and absorption, while 2% steel fiber volume fraction caused a significant reduction in the slope. Apparently, the steel fibers restricted the movement of water and occupied the larger void space in
the alkali-activated concrete structure. Other work noted similar conclusions in steel fiber-reinforced conventional cement-based concrete [107,108].

![Figure 18](https://via.placeholder.com/150)

**Figure 18.** Typical capillary sorptivity of alkali-activated concrete with slag:fly ash ratio of: (a) 3:1; (b) 1:1.

Typical absorption plots of alkali-activated concrete incorporating equal portions of slag and fly ash as a function of time are depicted in Figure 18b. Within the first 60 min (60 s^{0.5}), the slope of the sorptivity curve was higher than the remaining time of exposure. This is mainly a result of the corresponding early and late filling of large and small pores. An increase in RCA replacement percentage led to an increase in the slope and to higher water absorption, owing to the poor quality and porous nature of the RCA and its adhered old mortar. It is also possible that RCA may have cracks and fissures that had developed during the manufacturing process. The effect of steel fiber inclusion on the rate of water absorption was also examined. Higher steel fiber volume fractions led to lower slopes and water absorption.

Table 6 summarizes the sorptivity results of 28-day alkali-activated slag-fly ash blended concrete mixtures. The sorptivity values of plain concrete increased as more NA was replaced by RCA. Compared to the NA-based control, the replacement of 30%, 70%, and 100% RCA in alkali-activated concrete with a slag-to-fly ash ratio of 3:1 increased the sorptivity by 38%, 80%, and 125%, respectively. Conversely, mixtures with equal portions of slag and fly ash experienced increases of 40%, 80%, and 136%, respectively. Nevertheless, steel fiber incorporation decreased the sorptivity of the RCA-based mixtures, as they may have filled the concrete voids. On average, the addition of steel fibers by 1% and 2%, by volume, to concrete with a slag-to-fly ash ratio of 3:1 resulted in average decreases in the sorptivity of 5.1% and 14.4%, respectively, compared to that of RCA-based plain concrete mixtures. Counterparts made with slag:fly ash ratio of 1:1 noted decreases of 5.3% and 13.9%, respectively. The steel fibers may have reduced the absorption and sorptivity, owing to an improvement in the bond within the binding matrix [109] and/or reduction of voids [108,109]. Similar findings were reported in steel fiber-reinforced conventional cement-based NA and RCA concrete [53,107,108].

4.7. Non-Destructive Testing
4.7.1. Ultrasonic Pulse Velocity

The ultrasonic pulse velocity (UPV) can be employed in indirectly assessing the concrete quality and durability. The UPV results of alkali-activated slag-fly ash (3:1) blended concrete are presented in Figure 19a. Values were in the range of 4.6 and 6.6 km/s. An increase in RCA replacement in plain concrete mixtures to 30%, 70%, and 100% decreased the UPV by 5.7%, 14.7%, and 16.6%, respectively, owing to the cracks and voids in the RCA. These findings are synonymous with those reported in the mechanical properties. Still, the concrete quality of S75R0F0, S75R30F0, and S75R100F0 were categorized as “Excellent” based on IS 13311-1 [110] with UPV values above 4.5 km/s. Furthermore, the addition of
1% and 2% steel fibers, by volume, increased the UPV by, on average, 15.2% and 24.7%, respectively, compared to plain counterparts. The quality of steel fiber-reinforced concrete mixtures was also classified as “Excellent”.

![Figure 19](image.png)

**Figure 19.** (a) Ultrasonic pulse velocity of alkali-activated slag-fly ash blended concrete as a function of RCA replacement and (b) relationship between UPV and $f'_c$.

For mixtures made with equal portions of slag and fly ash, the replacement of NA by 30%, 70%, and 100% RCA led to 9.2%, 14.9%, and 16.6% reductions in UPV. As such, the quality of RCA-based mixtures was classified as “Good”, while that of the NA-based control (50SR0F0) was “Excellent”. Nevertheless, the incorporation of 1% and 2% steel fiber volume fractions increased the UPV by, on average, 28.7% and 38.0%, respectively. The results show that mixtures made with 30%, 70%, and 100% RCA required 1%, 2%, and 2% steel fiber volume fractions, respectively, to be classified with “Excellent” quality. Otherwise, their quality was considered to be “Good”.

Experimental UPV and $f'_c$ test results of alkali-activated slag concrete incorporating 25% and 50% fly ash were correlated using the scatter plots of Figure 19b and presented in the form of Equations (17) and (18), respectively. As the $R^2$ values for both relationships were noted to be 0.90, they can predict $f'_c$ from the UPV values presented in this work without the need for destructive experimental tests, signifying their importance to the construction industry.

\[
f'_c = 0.009v - 18.825 \quad (17)
\]

\[
f'_c = 0.016v - 53.317 \quad (18)
\]

4.7.2. Bulk Resistivity

The concrete bulk resistivity is an indirect measure of the concrete durability. Due to the conductive nature of steel fibers and their generation of unrepresentative results, mixtures incorporating steel fibers were not considered in the analysis. Accordingly, the results of the plain alkali-activated slag-fly ash blended concrete made with different RCA replacement percentages were considered, as shown in Figure 20. For mixtures incorporating 25% fly ash, the replacement of NA by 0, 30%, 70%, and 100% RCA resulted in bulk resistivity of 8.2%, 5.9%, 3.7%, and 3.6 kΩ·cm, respectively. The corresponding reductions are 28%, 55%, and 56% relative to the NA-based control mixture.

Additionally, mixtures made with 50% fly ash had bulk resistivity values ranging between 2.0 and 4.6 kΩ·cm. In fact, the bulk resistivity was found to decrease by 30%, 52%, and 57% compared to the control mixture when RCA replacement was 30%, 70%, and 100%, respectively. Similar to the mixtures with 25% fly ash, the most significant impact was noticed up to a replacement of 70%; however, a higher replacement percentage of 100% had limited effect. This is possibly due to the increase in the pore space of the...
alkali-activated matrix structure when 70% of NA was replaced by RCA to the extent that higher proportions of RCA replacement did not cause a further reduction.

![Graph](https://example.com/graph.png)

**Figure 20.** Bulk resistivity of alkali-activated slag concrete as a function of RCA replacement.

### 4.8. Abrasion Resistance

#### 4.8.1. Effect of RCA Replacement

Figure 21 shows typical abrasion mass loss of alkali-activated slag-fly ash blended concrete. Results of plain mixtures with a slag-to-fly ash ratio of 3:1 are depicted in Figure 21a. The replacement of NA by up to 30% RCA resulted in a nearly linear increase in the mass loss as a function of the number of revolutions. Yet, this was not the case with higher RCA replacements, where the slope of mass loss increased around 300 revolutions. As a result, the mass loss of 0, 30%, 70%, and 100% RCA mixtures were 35%, 43%, 73%, and 88%, respectively. It can thus be concluded that replacing NA with RCA negatively impacted the abrasion resistance of alkali-activated slag-fly ash blended concrete.

![Graph](https://example.com/graph2.png)

**Figure 21.** Typical abrasion resistance development profile of alkali-activated concrete with slag-fly ash ratio of: (a) 3:1; (b) 1:1.

Typical abrasion mass loss profiles of alkali-activated concrete with equal portions of slag and fly ash are illustrated in Figure 21b. The highest rate of mass loss was noted within the first 300 revolutions after which the rate tended to decrease. While the control mixture had a mass loss of 82% after 500 revolutions, those of mixtures made with 30, 70, and 100% RCA replacement were 82%, 95%, and 100%, respectively. This loss in performance is primarily owed to the higher porosity and inferior properties of RCA, the weak bond between the old and new paste, and the porous structure of the adhered mortar. Other work on conventional concrete made with RCA noted similar findings [53,111].
4.8.2. Effect of Steel Fiber Addition

Steel fiber-reinforced alkali-activated concrete mixtures with a slag-to-fly ash ratio of 3:1 noted a similar trend but with lower mass loss values. Indeed, mixtures incorporating 1% steel fiber, by volume, and 30%, 70%, and 100% RCA had mass losses of 27%, 57%, and 67%, respectively. In turn, 2% steel fiber volume fraction addition led to respective mass losses of 26%, 34%, and 36%, highlighting the less significant impact of RCA replacement on the abrasion resistance. Apparently, the incorporation of steel fibers enhanced the abrasion resistance of alkali-activated slag-fly ash (3:1) blended concrete to the extent that the mixture made with 100% RCA and 2% steel fiber, by volume, was comparable to that of the control.

The effect of adding steel fiber reinforcement on the abrasion resistance of alkali-activated concrete made with equal portions of slag and fly ash was examined. For mixtures incorporating 30% RCA, the addition of 1% and 2% steel fiber, by volume, reduced the abrasion mass loss by 28% and 38%, respectively, compared to the plain counterpart. Conversely, mixtures made with 70% and 100% RCA showed respective reductions of up to 33% and 19% upon adding steel fibers. This shows that the addition of steel fibers led to improved geometric integrity and a more densified alkali-activated concrete structure, evidenced by the water absorption and sorptivity results, capable of resisting abrasive and impact loading more effectively. In fact, the mixture made with 100% RCA and 2% steel fiber volume fraction showed comparable abrasion resistance to that of the control mixture.

4.9. Comparative Analysis

A comparative analysis of the results of alkali-activated concrete with slag:fly ash ratio of 3:1 and 1:1 was carried out. The cube compressive strength was determined at 1, 7, and 28 days to determine the strength development profile. At all ages, mixtures made with 25% fly ash had superior strength than counterparts made with 50% fly ash. This is believed to be owed to the accelerated reaction of calcium compounds in slag to produce calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) gels [86–89]. With lower slag content, such an accelerated reaction was less intense at an early age in alkali-activated concrete with equal portions of slag and fly ash. However, the subsequent strength increase was higher with an increase in fly ash content, owing to a predominantly lower 1-day $f_{cu}$ and delayed formation of sodium aluminosilicate hydrate gel (N-A-S-H) from the activation of fly ash at room temperature [91]. While the RCA replacement had a more detrimental impact on $f_{cu}$ of mixtures made with slag:fly ash of 3:1, the incorporation of steel fibers was more effective in the mixtures made with equal portions of slag and fly ash due to a weaker binding matrix. Conversely, the impacts of RCA replacement and steel fiber inclusion on $f'_{c}$ were more prominent in the latter mixture (slag:fly ash of 1:1). Apparently, the confinement effect of alkali-activated slag-fly ash blended concrete cubes under compressive loads was less critical with higher fly ash replacement (50%). In conclusion, alkali-activated concrete with slag:fly ash of 3:1 and 1:1 could be produced with 100% RCA without compromising $f_{cu}$ and $f'_{c}$ subject that 2% steel fiber, by volume, be incorporated in the mixture.

The compressive stress-strain response of alkali-activated concrete made with slag and fly ash at ratios of 3:1 and 1:1 was studied. Comparing the two sets of mixtures, it can be stated that the peak stress and strain of mixtures with 50% fly ash replacement were, on average, 23% lower and 173% higher than those of counterparts with 25% fly ash, owing to the slow activation reaction of fly ash at ambient conditions. The decreases in peak stress and increases in peak strain due to RCA replacement were more pronounced in mixtures with 50% fly ash replacement. For the same mixtures, the addition of steel fiber caused more prominent increases in the peak stress and peak strain.

The modulus of elasticity was reduced by, on average, 51% when increasing the fly ash replacement percentage from 25% to 50%, owing to more pore space, as evidenced by the higher water absorption. In turn, RCA replacement and steel fiber incorporation were more impactful on $E_c$ of alkali-activated slag-fly ash concrete with 50% fly ash. Actually,
the extent of increases in peak strain induced by steel fibers in mixtures made with 50% fly ash was significantly higher than the corresponding increases in peak stress. As a result, the slopes and $E_c$ values were lower.

As for splitting tensile strength, the increase in fly ash replacement from 25% to 50% caused a reduction in $f_{sp}$ of 27%. The replacement of NA by RCA had a more detrimental effect on $f_{sp}$ of mixtures made with 50% fly ash while being more influential on $f_c$ than $f_{sp}$. Conversely, steel fiber addition led to higher increases in $f_{sp}$ for these mixtures, owing to a weaker binder matrix. Despite this fact, they presented lower $f_{sp}$ values than counterparts with a slag-to-fly ash ratio of 3:1. Nevertheless, both mixtures could be produced with 100% RCA and 1% steel fiber, by volume, with superior performance to the NA-based control mixtures.

A comparison between the water absorption of alkali-activated concrete mixtures made with slag:fly ash ratios of 3:1 and 1:1 was also conducted. Results showed that former mixtures had lower water absorption than the latter, which is well-aligned with superior mechanical performance. Also, the RCA replacement and steel fiber addition were more influential on the latter mixtures relative to the former.

Non-destructive testing, comprising UPV and bulk resistivity, highlighted that mixtures with higher fly ash content had an inferior performance. In fact, all mixtures with a slag-to-fly ash ratio of 3:1 were classified to have “Excellent” concrete quality, while some mixtures with equal portions of slag and fly ash were considered to have “Good” concrete quality, based on IS 13311-1 [110]. Moreover, a similar negative effect of RCA replacement on UPV and bulk resistivity was noted for both mixtures (slag:fly ash of 3:1 and 1:1), while the influence of steel fiber incorporation on UPV was more significant in the latter.

The abrasion resistance was inversely proportional to the amount of fly ash in the mixture. Indeed, mixtures with 50% fly ash replacement experienced lower mechanical performance due to the slow activation reaction of fly ash at room temperatures, thereby negatively impacting the abrasion resistance. The respective negative and positive impacts of RCA replacement and steel fiber addition were slightly more pronounced with higher fly ash replacement.

5. Conclusions

The feasibility of utilizing recycled concrete aggregates and steel fibers to produce alkali-activated slag-fly ash blended concrete was examined. Based on the experimental test results, the conclusions can be drawn as follows:

- The 28-day cylinder compressive strength of plain alkali-activated concrete made with slag-to-fly ash ratio of 3:1 and 1:1 decrease by up to 50% and 54%, respectively, upon RCA replacement. Maximum respective strength reductions of 25% and 20% are recorded in the cube strength. This negative impact can be countered by steel fiber inclusion with up to 101% and 174% respective increases while noting a more significant impact at 1 day. As such, RCA replacement and steel fiber inclusion are generally more influential in mixtures with higher fly ash content. Nevertheless, increasing the fly ash content reduces the compressive strength.

- The confinement effect of alkali-activated slag-fly ash (3:1 and 1:1) blended concrete cubes under compressive loads is significantly influenced by RCA replacement but is less critical with higher fly ash replacement. As such, $f_c$ and $f_{cu}$ of each blended mixture are correlated through linear regression models to predict one property from the other with reasonable accuracy ($R^2 = 0.85$ and 0.95). These relationships offer a higher accuracy compared to models proposed in past work.

- Alkali-activated slag-fly ash (3:1) concrete mixtures incorporating dune sand can be produced with 30%, 70%, and 100% RCA replacement in conjunction with 0, 1%, and 2% steel fiber volume fractions, respectively, while sustaining a minor loss (<10%) in the design $f_c$ of 30 MPa. Conversely, mixtures made with equal portions of slag and fly ash experience limited loss (<6%) in design $f_c$ with 30%, 70%, and 100% RCA and
1%, 2%, and 2% steel fibers, by volume. Between the two binders, that with 25% fly ash presents more favorable results.

- As fly ash replacement increases, the peak stress of alkali-activated slag-fly ash blended concrete decreases while the peak strain increases. Further, the RCA replacement decreases the peak stress and increases the peak strain while steel fiber addition increases both parameters. Results show that these performance changes are more pronounced for peak strain and in mixtures with higher fly ash content.

- The modulus of elasticity of alkali-activated slag-fly ash (3:1 and 1:1) blended concrete decreases by up to 52% and 63%, respectively, upon replacement of NA by up to 100% RCA. The incorporation of up to 2% steel fibers, by volume, can enhance respective $E_c$ values by up to 18% and 41%, respectively. Clearly, the adverse impact of RCA replacement surpasses the positive influence of steel fiber addition. Still, the $E_c$ of the former are higher than the latter for all mixtures. Linear regression models were also developed to estimate the values of $E_c$. The prediction accuracy improves upon the inclusion of RCA replacement percentage and steel fiber volume fraction in the model. Codified equations cannot accurately estimate $E_c$.

- The splitting tensile strength decreases with higher fly ash replacement. The RCA replacement reduces $f_{sp}$ of alkali-activated slag-fly ash (3:1 and 1:1) blended concrete by up to 35% and 47%, respectively. Conversely, adding up to 2% steel fiber volume fraction increases $f_{sp}$ by up to 194% and 230%, correspondingly. It was found that RCA replacement and steel fiber addition have a more prominent impact on $f_{sp}$ than $f_c$. Based on the results, it is possible to produce alkali-activated slag-fly ash (3:1 and 1:1) blended concrete with 100% RCA in conjunction with 1% steel fiber, by volume, with superior $f_{sp}$ to that of the NA-based control. Regression models were developed to predict $f_{sp}$ from $f_c$, RCA replacement, and steel fiber volume fraction with high accuracy. Codified equations cannot accurately estimate $f_{sp}$.

- The UPV and bulk resistivity are reduced by up to 17% and 57%, respectively, with RCA replacement for both types of mixtures. Steel fiber addition increases the respective UPV values of mixtures made with slag-to-fly ash ratios of 3:1 and 1:1 by up to 25% and 38%. Also, former mixtures are classified to have excellent concrete quality regardless of RCA replacement and steel fiber addition, while latter plain and steel fiber-reinforced mixtures are classified to have good and excellent concrete quality, respectively.

- The RCA replacement leads to an increase in abrasion mass loss. This adverse effect of RCA can be countered by steel fiber addition. Yet, these impacts are slightly more pronounced with higher fly ash replacement. Alkali-activated slag-fly ash (3:1 and 1:1) concrete mixtures made with 100% RCA and 2% steel fiber, by volume, show comparable abrasion resistance to that of the NA-based control.

- The UPV and bulk resistivity are reduced by up to 17% and 57%, respectively, with RCA replacement for both types of mixtures. Steel fiber addition increases the respective UPV values of mixtures made with slag-to-fly ash ratios of 3:1 and 1:1 by up to 25% and 38%. Also, former mixtures are classified to have excellent concrete quality regardless of RCA replacement and steel fiber addition, while latter plain and steel fiber-reinforced mixtures are classified to have good and excellent concrete quality, respectively.

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