

Article

Properties of Steel Fiber-Reinforced Alkali-Activated Slag Concrete Made with Recycled Concrete Aggregates and Dune Sand

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Abstract: Reutilizing industrial by-products and recycled concrete aggregates (RCA) to replace cement and natural aggregates (NA) in concrete is becoming increasingly important for sustainable development. Yet, experimental evidence is needed prior to the widespread use of this sustainable concrete by the construction industry. This study examines the performance of alkali-activated slag concrete made with RCA and reinforced with steel fibers. Natural coarse aggregates were replaced with RCA. Steel fibers were added to mixes incorporating RCA at different volume fractions. Desert dune sand was used as fine aggregate. The mechanical and durability properties of plain and steel fiber-reinforced concrete made with RCA were experimentally examined. The results showed that the compressive strength did not decrease in plain concrete mixes with 30 and 70% RCA replacement. However, full replacement of NA with RCA resulted in a 20% reduction in the compressive strength of the plain mix. In fact, 100% RCA mixes could only be produced with compressive strength comparable to that of an NA-based control mix in conjunction with 2% steel fiber, by volume. In turn, at least 1% steel fiber, by volume, was required to maintain comparable splitting tensile strength. Furthermore, RCA replacement led to higher water absorption and sorptivity and lower bulk resistivity, ultrasonic pulse velocity, and abrasion resistance. Steel fiber incorporation in RCA-based mixes densified the concrete and improved its resistance to abrasion, water permeation, and transport, thereby enhancing its mechanical properties to exceed that of the NA-based counterpart. The hardened properties were correlated to 28-day cylinder compressive strength through analytical regression models.

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



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1. Introduction

Construction and demolition wastes (CDW) management is a global pressing issue. The massive amounts of debris generated in the demolition, construction, and renovation of structures are stretching landfill capacities and inducing economic leakages [1]. In the European Union, United Kingdom, United States, and China, over 800, 20, 500, and 200 million tons of CDW are produced annually, respectively [2–5]. Of this material, only around 20%, on average, is recycled, of which over 30% and 50% is masonry and concrete, correspondingly. Recycling of CDW offers a sustainable solution for reducing the production of these wastes while lowering the consumption rate of landfill sites and natural resources [6–8]. It has also been found to reduce the environmental footprint of construction [9,10]. For the past few decades, waste concrete has been reprocessed and reused as aggregate instead of natural aggregates (NA). The so-produced recycled concrete aggregate (RCA) consists of 65–70% original aggregate and 30–35% original cement paste, by volume [11]. However, the use of RCA in structural concrete has been restricted due to its lower compressive and tensile strength in comparison to those of NA-based

concrete [12]. RCA concrete also experiences more drying shrinkage and has inferior durability properties [13–15].

Other attempts have been made to improve the sustainability of concrete by reducing the consumption of cement. Indeed, the cement industry alone is accountable for 5–7% of the global CO₂ emissions [16,17], leading to an increase in the concentration of CO₂ in the atmosphere [18,19]. As a result, its production is becoming a critical global issue from an ecological, social, and environmental standpoint. To reduce the adverse impact of cement, it is crucial to find and utilize more sustainable substitutes. Fly ash, ground granulated blast furnace slag (or simply slag), silica fume, metakaolin, and others have partially replaced cement in conventional concrete. However, full replacement in typically hydrated concrete is not possible due to low performance. Instead, these materials can be activated in alkaline solutions to produce inorganic polymers, known as geopolymers [20].

Geopolymer or alkali-activated concrete has been found to be a suitable replacement to conventional ordinary Portland cement (OPC) concrete with equivalent or superior mechanical and durability properties [21–28]. Such performance is mainly attributed to the denser microstructure [21]. For alkali-activated slag concrete, the microstructure is typically composed of calcium silicate hydrate (C-S-H), hydrotalcite, and calcium aluminosilicate hydrate (C-A-S-H) [29–34]. In addition, the alkali-activated binder provides a stronger bond at the interfacial transition zone with the aggregates [35,36]. Accordingly, it is proposed to be a superior binder to OPC in concrete made with RCA. Past research reported that the alkali-activated RCA concrete experienced lower mechanical and durability properties compared to the NA-based counterpart due to the inferior properties of RCA compared with NA [37–44]. This loss in performance hinders its employability in engineering applications despite its potential to reduce the construction industry's environmental footprint.

In conventional cement-based concrete made with RCA, several methods were proposed to counter the performance reduction, including fiber incorporation [45–52]. A similar attempt has been made in alkali-activated or geopolymer mortars made with recycled fine aggregates. Nuaklong et al. [53] reported an improvement in mechanical properties of fly ash-based geopolymer mortar made with fine RCA upon inclusion of micro carbon fiber. This shows that fiber inclusion in alkali-activated concrete will likely improve its properties. Yet, limited information is available in the literature on the performance enhancement of alkali-activated slag concrete made with RCA through the incorporation of fiber reinforcement.

This research aims to examine the combined effect of RCA replacement and steel fiber incorporation on the mechanical and durability characteristics of alkali-activated slag concrete. The validity of empirical relations available in the literature and codified equations to predict the performance of so-produced concrete was examined. It is hypothesized that the inclusion of a certain steel fiber volume fraction could allow the full replacement of NA by RCA without compromising the performance. This study also offers cutting-edge material characterization of steel fiber-reinforced RCA alkali-activated slag concrete and plays a critical role in the development of sustainable concrete for structural applications.

2. Materials and Methods

Ten alkali-activated slag concrete mixes were proportioned and prepared. The variables included the RCA replacement percentage (30, 70, and 100%) and steel fiber volume fraction (0, 1, and 2%). Dune sand served as the fine aggregate to highlight the contribution towards sustainable development. The experimental program entailed the evaluation of hardened concrete properties. It was conducted using cubes (100 mm), cylinders (100 mm diameter × 200 mm height), and discs (100 mm diameter × 50 mm height). According to Mehta [54] and ACI Committee 201.2 [55], the durability of concrete can be estimated through its resistance to penetration of aggressive ions and abrasive loads. The former is characterized by absorption, sorptivity, bulk resistivity, and ultrasonic pulse velocity, while the latter is assessed by the Los Angeles (LA) abrasion test. This section

further describes the materials used, alkali-activated slag concrete mix design, sample preparation, and experimental testing procedures.

2.1. Materials

Ground granulated blast furnace slag was employed as the main binder in the alkali-activated concrete mixes with a Blaine fineness of $4250 \text{ cm}^2/\text{g}$ and a specific gravity of 2.70. Desert dune sand served as a sustainable fine aggregate. Table 1 summarizes their chemical compositions, obtained using X-ray fluorescence, and physical properties. Further, their particle size distribution, scanning electron microscopy (SEM) micrographs, and X-ray diffraction (XRD) spectra are shown in Figures 1–3, respectively. The SEM and XRD highlight the fine, irregular slag's amorphous structure, with peaks of quartz (SiO_2), mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$), and gehlenite ($\text{Ca}_2\text{Al}[\text{AlSiO}_7]$). In turn, the dune sand is characterized by crystalline irregular particles composed mainly of quartz with traces of calcite (CaCO_3), ferric oxide (Fe_2O_3), and aluminum oxide (Al_2O_3).

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

Oxides	Material (%)	
	Slag	Dune Sand
CaO	42.0	14.1
SiO_2	34.7	64.9
Al_2O_3	14.4	3.0
MgO	6.9	1.3
Fe_2O_3	0.8	0.7
loss on ignition	1.1	0.0
others	0.2	16.0
Physical properties		
Blaine fineness (cm^2/g)	4250	-
specific gravity	2.70	2.77

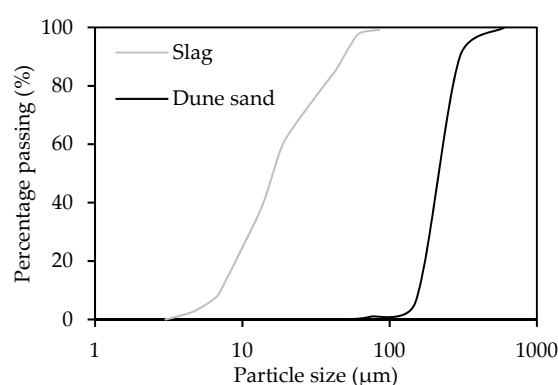


Figure 1. Particle size distribution of slag and dune sand.

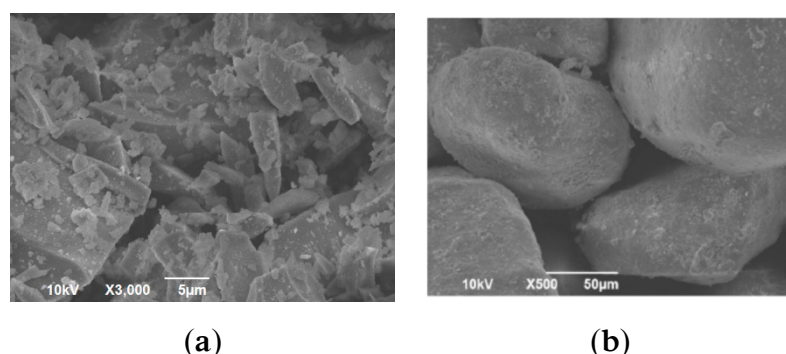


Figure 2. SEM micrographs of (a) slag and (b) dune sand.

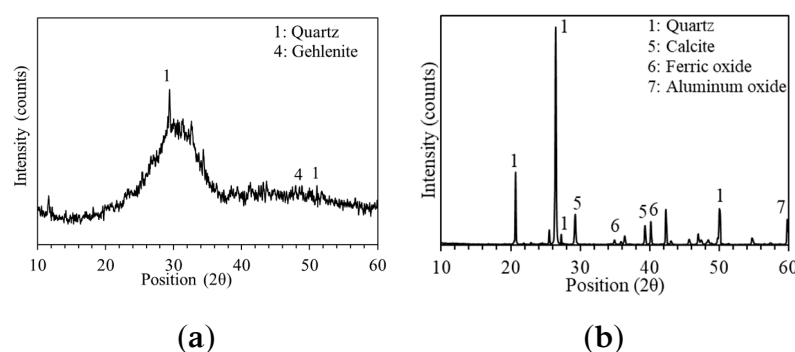


Figure 3. XRD patterns of (a) slag and (b) dune sand.

The coarse aggregates used in this work were in the form of natural crushed dolomitic limestone coarse aggregates and recycled concrete aggregates. The natural aggregates were obtained from a local quarry with a nominal maximum size (NMS) of 20 mm, while the recycled counterparts were sourced from a local recycling plant with a similar NMS, in their as-received conditions. Indeed, the recycling plant crushed construction and demolition waste from old concrete structures with unknown strength without chemically or mechanically treating it. The grading curves of both aggregates and their corresponding blends are illustrated in Figure 4. It is worth noting that all curves satisfied the limits set by ASTM C33 [56]. Further, the physical properties of the two types of coarse aggregates, along with the dune sand, are shown in Table 2. The dry-rodded density and specific gravity of RCA were lower than those of NA, owing to the porous mortar attached to the surface of the RCA particles. In turn, the absorption, abrasion mass loss, and soundness were higher in RCA than NA. This highlights the relatively weaker nature of the former compared to the latter. While all the properties were within the acceptable limits of the ASTM standards and/or design codes [57–60], the water absorption of RCA was found to be beyond these limits. Nevertheless, the absorption of aggregates was accounted for by attaining saturated surface dry (SSD) conditions prior to incorporation into the mixes.

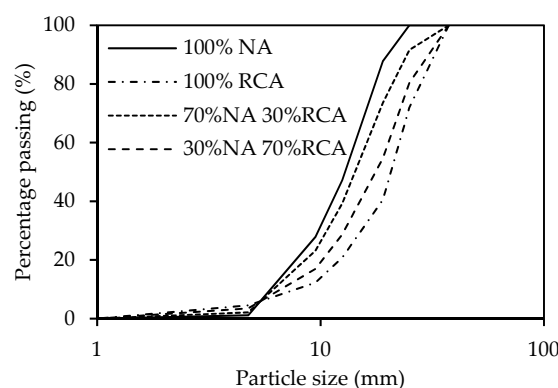


Figure 4. Particle size distribution of different mixes of NA and RCA.

Table 2. Physical properties of fine and coarse aggregates.

Property (Unit)	ASTM Test	Dune Sand	NA	RCA
dry-rodded density (kg/m^3)	C29 [60]	1663	1635	1563
absorption (%)	C127 [61]	-	0.22	6.63
Los Angeles abrasion (%)	C131 [57]	-	16.0	32.6
surface area (cm^2/g)	C136 [62]	116.80	2.49	2.50
soundness (MgSO_4 , %)	C88 [58]	-	1.20	2.78
specific gravity	C127 [61]	2.77	2.82	2.63
fineness modulus	C136 [62]	1.45	6.82	7.44

The alkaline activator solution consisted of sodium hydroxide (SH) and sodium silicate (SS). The SH was in the form of 97–98% pure sodium hydroxide flakes and was dissolved in tap water to attain a solution with a molarity of 14M. This molarity was based on the optimization experiments conducted in previous research [63–66]. In comparison, the SS solution was Grade N with a mass chemical composition of 26.3% SiO_2 , 10.3% Na_2O , and 63.4% H_2O . Also, a polycarboxylic superplasticizer (SP) was used to maintain the workability of alkali-activated concrete without affecting its mechanical performance [67,68].

Double hooked-end steel fibers, shown in Figure 5, were added to the alkali-activated concrete mixes. Their geometric and physical properties, as provided by the manufacturer, are summarized in Table 3 [69]. The volume fraction was limited to 2%, as trial mixes with 3% steel fibers, by volume, could not be properly cast.



Figure 5. Geometry of steel fibers.

Table 3. Geometric and physical properties of steel fibers (as provided by the manufacturer [69]).

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 fiber	0.55	35	65	7.9	14.531	1345	210

2.2. Mixture Proportioning

Table 4 summarizes the mixture proportions of alkali-activated slag concrete. A total of ten mixtures were designed to evaluate the effect of replacing NA with RCA and the incorporation of steel fibers on the performance of alkali-activated slag concrete. Replacements of NA by RCA were altered by 0, 30, 70, and 100%, while the steel fiber volume fraction varied by 0, 1, and 2%. In the absence of consistent mix design guidelines, the contents of slag, dune sand (DS), coarse aggregates (NA and RCA), SS, SH, and SP were optimized to attain a 30-MPa concrete control mix based on trial mixes. They were 300, 725, 1210, 99, 66, and 10.5 kg/m³, respectively. In turn, the steel fibers varied from 0 to 78 and 156 kg/m³, representing a 0 to 1 and 2% addition, by volume. Samples were designated as RXSFY, whereby X and Y denoted the percentage of RCA replacement, by mass, and the steel fiber volume fraction. For example, the mix made with 30% RCA and 2% steel fiber, by volume, is labeled as R30SF2.

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

Mix No.	Mix Designation	Mass (kg/m ³)							
		Slag ¹	DS ¹	NA ¹	RCA ¹	SS ¹	SH ¹	SP ¹	SF ¹
1	R0SF0	300	725	1210	0	99	66	7.5	0
2	R30SF0	300	725	847	363	99	66	7.5	0
3	R30SF1	300	725	847	363	99	66	7.5	78
4	R30SF2	300	725	847	363	99	66	7.5	156
5	R70SF0	300	725	363	847	99	66	7.5	0
6	R70SF1	300	725	363	847	99	66	7.5	78
7	R70SF2	300	725	363	847	99	66	7.5	156
8	R100SF0	300	725	0	1210	99	66	7.5	0
9	R100SF1	300	725	0	1210	99	66	7.5	78
10	R100SF2	300	725	0	1210	99	66	7.5	156

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

2.3. Sample Preparation

Alkali-activated slag concrete specimens were prepared and cast under ambient laboratory conditions of 23 ± 2 °C and a relative humidity of 50 ± 5%. The alkaline activator solution was prepared 24 h prior to casting to allow for heat dissipation from the reactions of SH flakes with water and then the 14M-SH solution with the SS solution. The dry components, including the coarse aggregates, dune sand, and slag, were mixed in a pan mixer for 3 min. In mixes entailing the use of steel fibers, they were added to the dry components to ensure proper dispersion. The superplasticizer was added to the wet components prior to being gradually incorporated into the dry components of the mix. The wet and dry components were mixed in the pan mixer for another 3 min to ensure homogeneity. The fresh alkali-activated concrete was then placed in two to three layers into 100 mm diameter × 200 mm height cylinders and 100-mm cubes and vibrated on a vibrating table for 5–10 s per layer, as per ASTM C192 [70]. The cast specimens were then left to air-cure until testing age to simulate an on-site construction setting. For each test, three replicate specimens per mix were prepared.

2.4. Experimental Methods

The compressive strength of concrete was determined using a Wykeham Farrance machine with a loading capacity of 2000 kN. An axial compression load was applied to cylindrical (100 mm diameter × 200 mm height) and cube (100 mm) alkali-activated concrete specimens at a rate of 7 kN/s until failure, as per ASTM C39 [71] and BS EN 12390-3 [72], respectively. The resulting respective compressive strengths were denoted as f'_c and f_{cu} . While f'_c was measured at the age of 28 days, f_{cu} was determined at 1, 7, and 28 days.

The modulus of elasticity (E_c) indicates the concrete's resistance to deformation under an applied compression load. As per the procedure of ASTM C469 [73], a 500-kN load cell recorded the applied load, and four 60-mm-long strain gauges attached to the sides of the 100 mm × 200 mm (diameter × height) cylinder at diametrically opposite locations recorded the strain. The modulus of elasticity was then calculated at 28 days as per Equation (1),

$$E_c = \frac{S_2 - S_1}{\varepsilon_2 - 0.00005} \quad (1)$$

where E_c is the chord modulus of elasticity in (MPa), S_2 is stress corresponding to 40% of ultimate load, S_1 is stress corresponding to a longitudinal strain ε_1 of 50 millionths in (MPa), and ε_2 is the longitudinal strain produced by stress S_2 . Triplicate specimens were also used to obtain an average.

The tensile splitting strength (f_{sp}) of alkali-activated slag concrete was determined according to the procedure of ASTM C496 [74]. A Wykeham Farrance machine with a loading capacity of 2000 kN applied the load at a rate of 1 kN/s to cylindrical specimens (100 mm diameter × 200 mm height).

The water absorption was determined using 100 mm × 50 mm (diameter × height) alkali-activated slag concrete discs at the age of 28 days, as per ASTM C642 [75]. The test specimens were oven-dried for 24 h at 105 °C and weighed until a mass change of less than 0.5% was obtained. They were then placed in a water container for 24 h, after which their saturated surface dry (SSD) mass was recorded. Equation (2) was employed to calculate the water absorption:

$$\text{Water absorption (\%)} = \frac{\text{SSD mass (g)} - \text{Oven-dried mass (g)}}{\text{Oven-dried mass (g)}} \times 100\% \quad (2)$$

Sorptivity was conducted following the procedure of ASTM C1585 [76]. The test was carried out on 28-day alkali-activated slag concrete disc specimens (100 mm diameter × 50 mm height). The test specimens were first vacuum-saturated and preconditioned as per the recommendations of ASTM C1202 [77]. After obtaining the initial mass, the sample's mass was recorded at 1, 5, 10, 15, 20, 30, and 60 min, and then after every hour until 6 h. The absorption was calculated using Equation (3) and plotted against the square root of time. The slope of the best-fit relationship from 1 min to 6 h represented the initial sorptivity. The test was to be repeated if the regression coefficient, R^2 , was less than 0.98, as per ASTM C1585 [76].

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

Bulk resistivity is a non-destructive test that relates the concrete's ability to resist chloride ion diffusion under an electric current to its general quality, durability, and performance. Indeed, the durability is governed by the rate of penetration of these aggressive ions into the concrete [54]. The test was conducted on 28-day alkali-activated slag concrete cylinder samples in accordance with ASTM C1876 [78]. The bulk resistivity was calculated using Equation (4). Owing to their electrically conductive nature, steel fibers may give misleading results. As such, only plain alkali-activated concrete samples were examined.

$$\text{Bulk Resistivity (}\Omega\cdot\text{cm)} = \frac{\text{Applied voltage (V)} \times (\text{Avg. sample diameter (mm)})^2}{1273.2 \times \text{Current at 1 min (mA)} \times \text{Avg. sample length (mm)}} \quad (4)$$

Ultrasonic pulse velocity was used to assess the general quality and integrity of the concrete by indirectly estimating the content of voids, cracks, and imperfections in the 28-day alkali-activated slag concrete structure. The direct UPV test was carried out on three cube samples (100 mm) per mix, according to ASTM C597 [79].

The abrasion resistance test provides an estimate of the general quality and durability of concrete through its resistance to abrasion, impact, and friction [54,55]. It is mainly dependent on the strength of the binding matrix and aggregate, in addition to the bond between these two components [80,81]. The test was conducted using a Los Angeles (LA) abrasion testing machine in accordance with ASTM C1747 [82]. The mass of the 28-day disc specimens (100 mm diameter $\times$ 50 mm height) was recorded before starting the test and after each subsequent 100 revolutions. The mass loss percentage over 500 revolutions represented the alkali-activated slag concrete abrasion resistance potential.

Analytical regression models were developed using the regression data analysis tool in Microsoft Excel to correlate relevant concrete characteristics, including cylinder compressive strength, cube compressive strength, modulus of elasticity, splitting tensile strength, and ultrasonic pulse velocity. The accuracy of the developed relations was measured in terms of the correlation coefficient (R^2).

3. Results and Discussion

3.1. Compressive Strength

The effect of RCA replacement and steel fiber inclusion on the cube compressive strength (f_{cu}) of alkali-activated slag concrete is shown in Figure 6. At the age of 1 day, the replacement of 30% RCA had no impact on the strength of plain concrete, as presented in Figure 6a. However, higher replacements of 70 and 100% reduced the strength from 38.6 MPa to 26.4 and 21.8 MPa, representing decreases of 32 and 44%, respectively. This is primarily owed to the weak interfacial bond between the alkali-activated matrix and RCA alongside the porous nature of the RCA. Other work on alkali-activated fly ash and slag mortars and concrete made with recycled aggregates noted analogous findings [37–44]. Nevertheless, the addition of 1 and 2% steel fiber volume fractions could enhance the 1-day compressive strength by, on average, 21 and 30%, respectively, in comparison to the plain concrete, as presented in Figure 6b,c. Indeed, with up to 70% RCA replacement and 2% steel fiber volume fraction, the 1-day strength was comparable to that of the control mix. In turn, mixes having 100% RCA with and without steel fibers had lower 1-day strength than the control, owing to the predominantly negative impact of RCA.

At the age of 7 and 28 days, the replacement of NA by RCA led to strength loss of up to 23 and 20%, respectively. Similar findings were reported in alkali-activated concrete made with single or multiple binders [28,39,41]. Clearly, the impact of RCA replacement was most critical at an early age and became less apparent at a later age. This is due to the development of reaction products over time, as noted in other work [34]. The addition of steel fibers improved the respective 7- and 28-day strengths by up to 18 and 21%, on average, owing to the denser alkali-activated matrix and reduced pore space, which is attributed to the lower water absorption and sorptivity, as shown later. Furthermore, the bridging effect of the steel fibers seems to have led to an enhancement in the structural integrity of the alkali-activated slag concrete. Analogous improvement in compressive strength was noted in other studies on steel fiber-reinforced NA-based alkali-activated concrete [83,84]. Compared with the values obtained at the age of 1 day, the improvement in f_{cu} due to steel fiber inclusion was lower, highlighting the superior effect of steel fibers at an early age. Based on these results, it can be concluded that alkali-activated slag concrete mixes incorporating dune sand could be made with up to 70% RCA without steel fibers and 100% RCA with 2% steel fibers, by volume, while sustaining insignificant loss (<3%) in 28-day cube compressive strength. In comparison, conventional 30-MPa cement-based concrete required 0, 1, and 3% steel fiber volume fractions to sustain a limited loss in compressive strength when 30, 70, and 100% NA was replaced by RCA, respectively [50]. This shows that alkali-activated slag is a more suitable binder than OPC in concrete made with more than 30% RCA, possibly due to better interlock with the RCA. Indeed, other work has found that alkali-activated binders provide a stronger bond at the interfacial transition zone with natural aggregates [35,36].

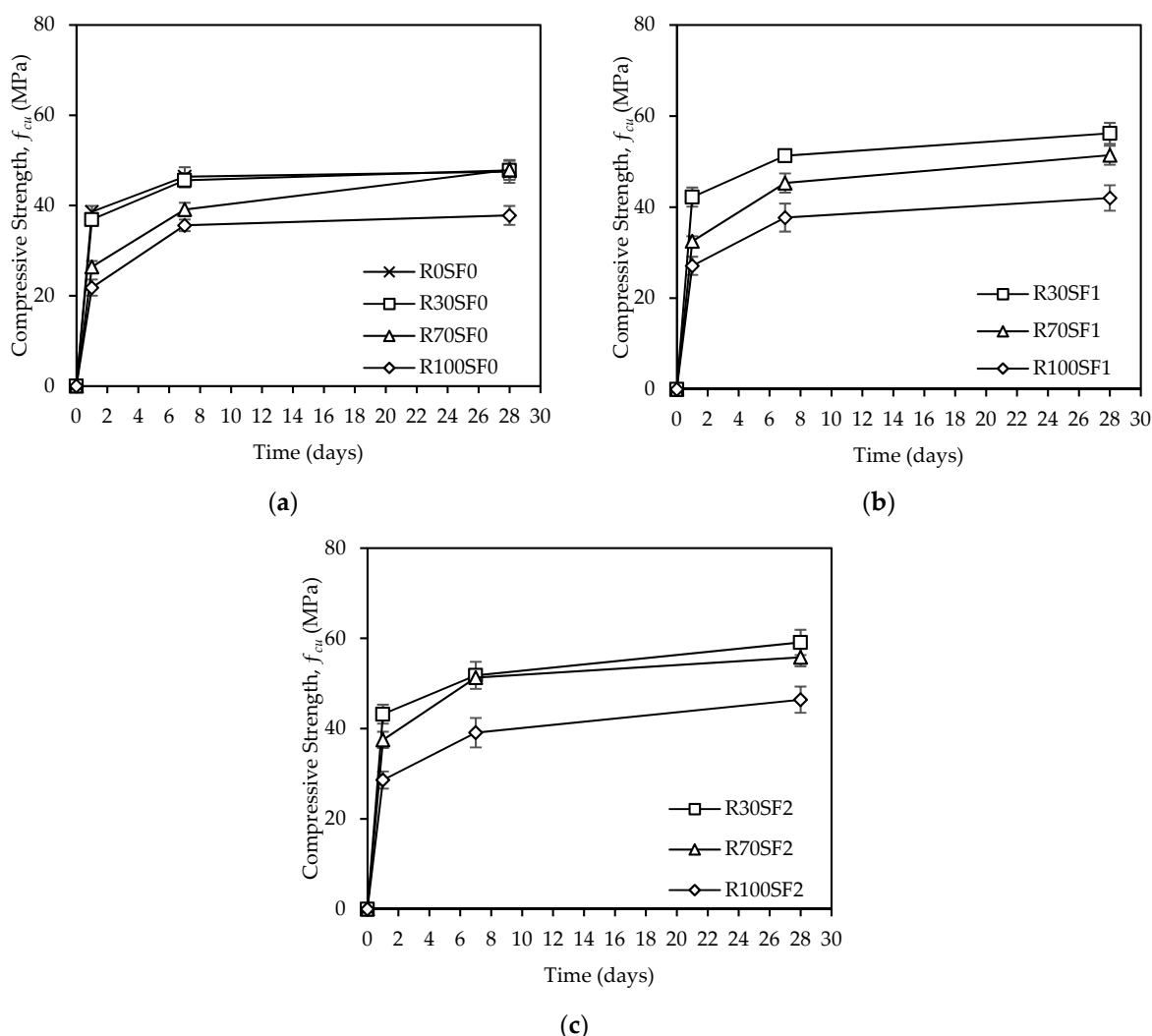


Figure 6. Development of cubic compressive strength of alkali-activated slag concrete mixes: (a) SF 0%; (b) SF 1%; (c) SF 2%.

The cube compressive strength (f_{cu}) of alkali-activated slag concrete was measured at the ages of 1, 7, and 28 days to examine strength development over time. Mixes were made with different RCA replacement percentages and steel fiber volume fractions. Table 5 presents the results. The control mix R0F0 had 1-, 7-, and 28-day compressive strengths of 38.6, 46.4, and 47.5 MPa, respectively. As such, the increase from 1 to 7 days was 20% while that from 7 to 28 days was only 2%. Clearly, the activation reaction mainly took place during the first 7 days with 1- and 7-day strengths being 81 and 98% that at 28 days. This is due to the accelerated reaction of calcium-carrying compounds in slag to form calcium aluminosilicate hydrate (C-A-S-H) and calcium silicate hydrate (C-S-H) gels [29–32] and the high molarity of the SH solution [85]. Yet, such a reaction seemed to slow down after 7 days. Furthermore, the strength development profile of alkali-activated slag concrete mixes incorporating RCA was examined. Higher RCA replacement percentages led to higher increases in strength from 1 to 7 days with mixes R30SF0, R70SF0, and R100SF0 exhibiting 23, 48, and 63% increases over this time period. Similar to the control mix, the main increase in strength was within the first 7 days, while a lesser increase was noted from 7 to 28 days. It appears that the weak bond between the binder matrix and RCA was responsible for the low early strength. Yet, as the activation reaction progressed, the bond improved and the strength increased. In contrast, increasing the steel fiber volume fraction led to a decrease in the strength gain within the first 7 days. In fact, the cube compressive strength (f_{cu}) of mixes incorporating 0, 1, and 2% steel fibers, by volume, increased by,

on average, 45, 33, and 31% from 1 to 7 days. Conversely, the strength increased by, on average, 11, 12, and 14% from 7 to 28 days. Apparently, steel fibers had such a significant impact on the 1-day strength, as shown earlier, that the increase in strength over time was lesser than that of plain counterparts.

Table 5. Compressive strength of alkali-activated slag concrete mixes.

Mix No.	Mix Designation	f_{cu} (MPa)			f'_c (MPa)	Increase 1–7 ^a (%)	Increase 7–28 ^b (%)	f'_c/f_{cu}
		1-Day	7-Day	28-Day				
1	R0SF0	38.6	46.4	47.5	31.8	20.2	2.4	0.67
2	R30SF0	36.9	45.6	47.8	30.0	23.6	4.8	0.63
3	R30SF1	42.2	51.3	56.2	34.2	21.6	9.6	0.61
4	R30SF2	43.2	51.8	59.1	36.4	19.9	14.1	0.62
5	R70SF0	26.4	39.1	47.9	30.4	48.1	22.5	0.63
6	R70SF1	32.5	45.3	51.4	31.9	39.4	13.5	0.62
7	R70SF2	37.5	51.3	55.8	33.3	36.8	8.8	0.60
8	R100SF0	21.8	35.6	37.8	25.0	63.3	6.2	0.66
9	R100SF1	27.1	37.7	42.0	28.0	39.1	11.4	0.67
10	R100SF2	28.6	39.1	46.4	30.1	36.7	18.7	0.65

^a Percent increase in f_{cu} from 1 to 7 days, ^b Percent increase in f_{cu} from 7 to 28 days.

In addition, Table 5 highlights the effect of RCA replacement and steel fiber incorporation on the 28-day cylinder compressive strength (f'_c) of alkali-activated slag concrete. An increase in the RCA replacement percentage to 30, 70, and 100% led to respective decreases of 5, 5, and 21% in f'_c , possibly owing to a weak interface between the aggregate and alkali-activated slag paste and/or poor quality and presence of voids and cracks in the RCA [50]. Compared to the 28-day cube compressive strengths, the loss in cylinder strength was more pronounced, especially for 30 and 70% RCA replacement. The addition of 1 and 2% steel fibers, by volume, enhanced f'_c of the plain RCA alkali-activated slag concrete by up to 14 and 21%, respectively, thus providing evidence for the ability to reverse the negative impact of RCA replacement using steel fibers. Indeed, alkali-activated slag mixes can attain the design cylinder compressive strength of 30 MPa with 30, 70, and 100% RCA replacement in conjunction with 0, 0, and 2% steel fiber volume fractions.

The f'_c -to- f_{cu} ratio of alkali-activated slag concrete is also presented in Table 5. The control mix R0F0 had a ratio of 0.67. The replacement of NA by 30 and 70% RCA slightly decreased the ratio while 100% replacement generally had almost no impact. On the other hand, the addition of steel fibers did not significantly affect the ratio with values being in the range of plain counterparts. Apparently, the confinement effect of cubes under compressive loads was unaffected by RCA replacement. Based on these findings, it is clear that the 28-day cylinder and cube compressive strengths of alkali-activated slag concrete can be correlated. Such correlation is important to provide a prediction of one property from the other rather than measuring both properties in accordance with ASTM C39 [71] and BS EN 12390-3 [72]. The relationship between these properties is illustrated in Figure 7a and presented in Equation (5). Using this analytical relationship and with correlation coefficient $R^2 = 0.85$, it is possible to predict f'_c from f_{cu} (or vice versa) of this work with reasonable accuracy. Compared with ordinary Portland cement concrete, which has an f'_c -to- f_{cu} ratio in the range of 0.65–0.90 [86], the ratio obtained herein is slightly lower. Yet, the accuracy of the relationship could be improved ($R^2 = 0.95$) with the addition of an intercept, as shown in Equation (6), which could be employed for the range of f_{cu} results presented herein.

$$f'_c = 0.63f_{cu} \quad (5)$$

$$f'_c = 0.48f_{cu} + 7.70 \quad (6)$$

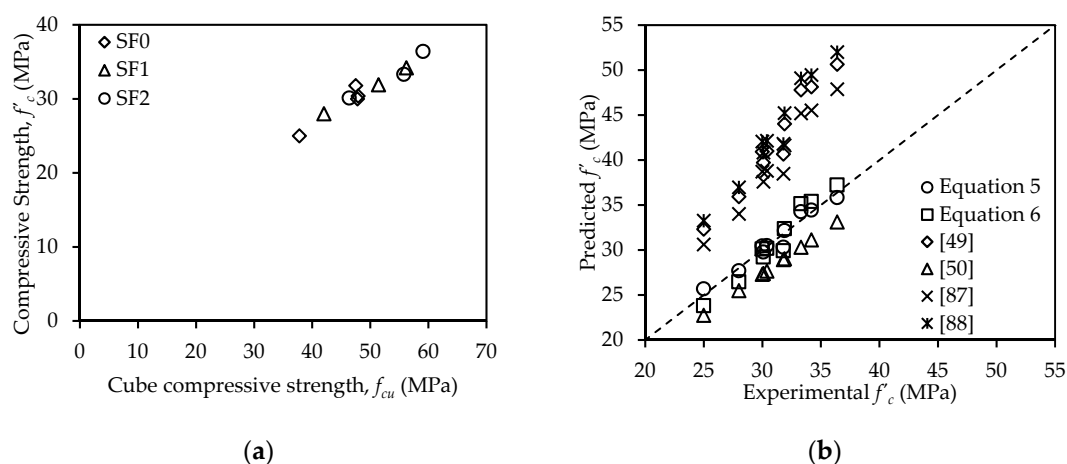


Figure 7. (a) Relationship between cubic and cylinder compressive strengths and (b) predicted versus experimental cylinder compressive strength.

Past literature developed similar equations to predict the cylinder compressive strength from the cube compressive strength for conventional cement-based concrete incorporating RCA and steel fibers [49,50,87,88]. The employability of these equations for alkali-activated slag concrete is assessed. Figure 7b shows that equations by Gao, Zhang, and Nokken [49], Xiao, Li, and Zhang [87], and Xie, Guo, Liu, and Xie [88] overestimated the value of f'_c , while that developed by Kachouh, El-Hassan, and El-Maaddawy [50] provided a reasonably accurate prediction. In turn, Equations (5) and (6) proposed in this study provided the highest accuracy.

3.2. Compressive Stress-Strain Response

Figure 8 illustrates typical compression stress-strain curves of alkali-activated slag concrete mixes made with RCA replacement and steel fibers. For concrete mixes made with 30, 70, and 100% RCA, the respective peak stress was, on average, 11, 22, and 20% higher with every 1% steel fiber added, by volume. Compared to cement-based concrete mixes with similar design strength, these increases in peak stress due to steel fiber inclusion are more significant [50]. In turn, the slope and peak strain (strain at peak load) increased by, on average, 20 and 147% with the addition of steel fibers, respectively. With such increases in peak strain, it is clear that the incorporation of steel fibers mainly impacted the deformability of alkali-activated RCA concrete mixes.

From Figure 8, it can also be seen that a decrease in the slope and peak stress was noted as more RCA was replaced in the mix. In fact, mixes made with 0, 1, and 2% steel fibers showed decreases in peak stress of 2.5, 1.8, and 1.3% for every 10% RCA replaced in the mixes, owing to the general weaker and porous nature of RCA and a lower concrete modulus of elasticity. Similar findings were reported in other work on cement-based concrete [50,87,89–92]. Conversely, the respective peak strains for mixes made with 0, 1, and 2% steel fibers increased by, on average, 11, 5, and 4% for every 10% RCA replacement. This is attributed to the fact that lower strength concrete has higher strain at peak load.

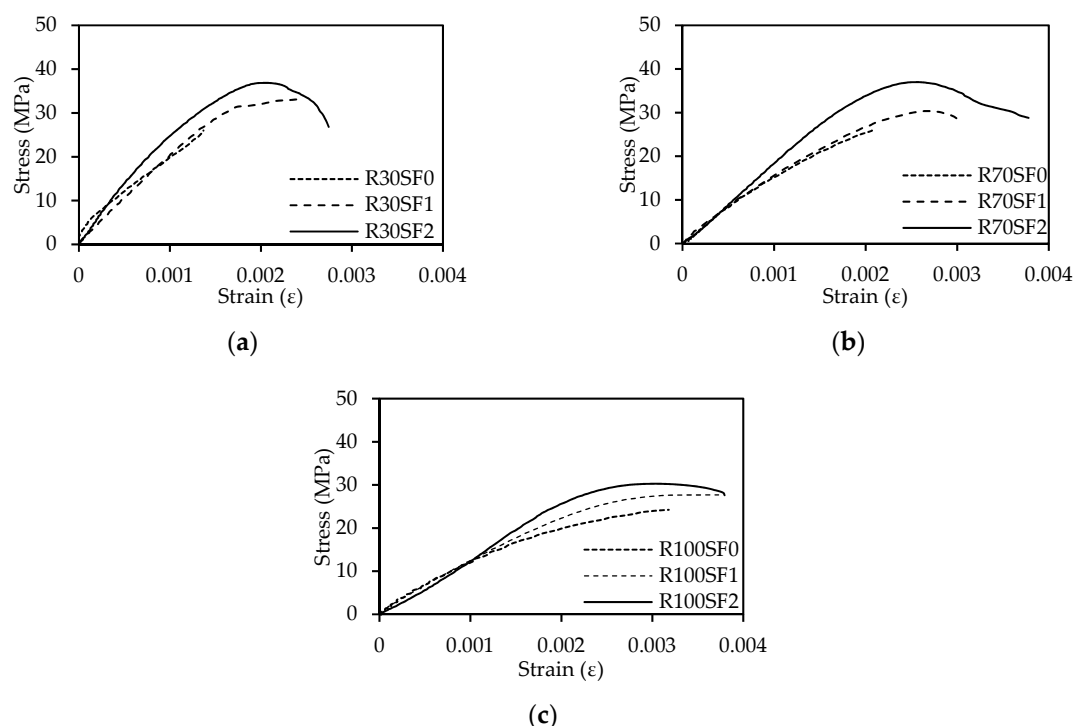


Figure 8. Typical compression stress-strain curves of alkali-activated slag concrete mixes with steel fiber volume fractions of (a) 0%, (b) 1%, and (c) 2%.

3.3. Modulus of Elasticity

The modulus of elasticity, E_c (in GPa), of 28-day alkali-activated slag concrete is presented in Figure 9. The replacement of NA by RCA led to a decrease in the values of E_c . Plain alkali-activated slag concrete mixes made with 30, 70, and 100% RCA had 42, 44, and 56% lower E_c than that of the control mix, respectively, due to the weak interfacial bond between the aggregate and old mortar and porous structure of the RCA. Other researchers have reported similar losses in E_c upon RCA replacement [26,44,89]. Nevertheless, steel fiber inclusion could alleviate this reduction. In fact, the addition of 1% steel fiber, by volume, to mixes made with 30, 70, and 100% RCA led to respective increases in E_c of 13, 11, and 28%, while 2% steel fiber volume fraction increased E_c by 43, 36, and 32%, respectively. Such an increase in E_c is mainly attributed to the steel fibers' ability to densify the matrix and reduce pore space, as evidenced by the water absorption results, and their bridging capabilities, which delays the initiation and propagation of microcracks under compression loading. Still, none of the mixes incorporating RCA and steel fibers could attain the modulus of elasticity of the control mix. This shows that while steel fibers could enhance the modulus of elasticity, the adverse effect of RCA replacement was more pronounced.

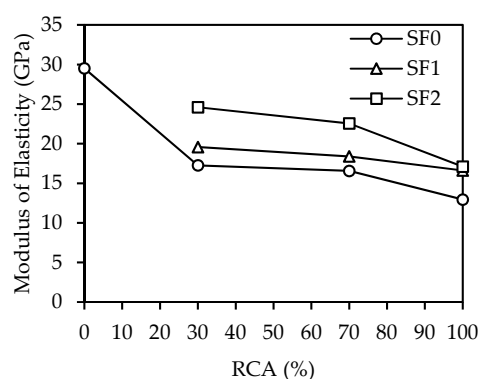


Figure 9. Modulus of elasticity of alkali-activated slag concrete mixes with different RCA replacement percentages and SF volume fractions.

The modulus of elasticity and 28-day cylinder compressive strength of alkali-activated slag concrete were correlated. A linear regression model was developed for test results from this work using the scatter plot of Figure 10a and formulated into Equation (7) in a form similar to that proposed by ACI 363 [90]. The low correlation coefficient, R^2 , of 0.48 signifies a relatively high scatter between the two properties. As such, a multivariable linear regression model was proposed in the form of Equation (8) to include the effect of RCA and steel fibers (SF). From Equation (8), it can be noted that the modulus of elasticity was proportional to the 28-day cylinder compressive strength and the steel fiber volume fraction but was inversely proportional to the RCA replacement. This is indicative of the respective positive and negative effects of steel fibers and RCA on the value of E_c of alkali-activated slag concrete. With an R^2 value above 0.90, Equation (8) can accurately predict E_c for the range of f'_c values presented in this work.

$$E_c = 11.4\sqrt{f'_c} - 44.0 \quad (7)$$

$$E_c = 4.24\sqrt{f'_c} - 0.09\text{RCA} + 1.10\text{SF} \quad (8)$$

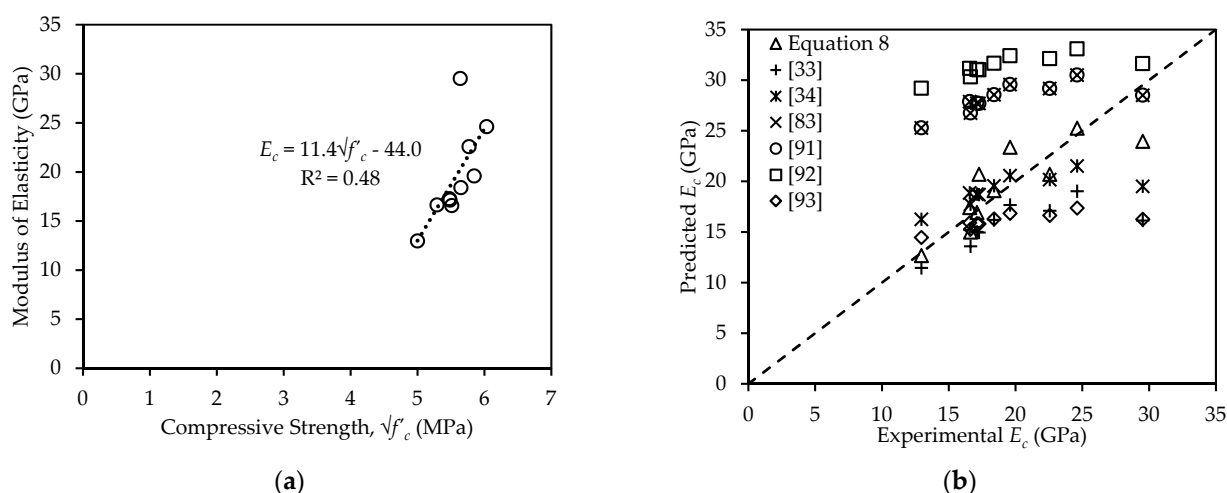


Figure 10. (a) Relationship between modulus of elasticity and cylinder compressive strength and (b) predicted versus experimental modulus of elasticity.

The modulus of elasticity can be typically predicted from codified equations, including those of ACI Committee 318 [91], CEB-FIP [92], and AS3600 [93]. In addition, other research on plain and steel fiber-reinforced alkali-activated concrete proposed equations to relate E_c to f'_c [33,34,83]. The feasibility of using these equations is evaluated while also considering

the newly-developed relationship in Equation (8). Figure 10b shows that the equations of ACI Committee 318 [91], El-Hassan and Elkholy [83], and CEB-FIP [92] over-estimate the values of E_c for alkali-activated slag concrete, while the remaining [33,34,93] provided a more accurate prediction for E_c up to 20–25 GPa, beyond which the accuracy diminished. Nevertheless, Equation (8) proved to be most accurate at predicting E_c with scatter plots converging around the 45° line. It is thus clear that some codified equations and those proposed in the literature may be suitable for predicting E_c from f'_c with reasonable accuracy despite the addition of steel fibers and RCA.

3.4. Splitting Tensile Strength

The tensile properties of alkali-activated slag concrete were indirectly evaluated using the 28-day splitting tensile strength (f_{sp}), as shown in Figure 11. An increase in RCA replacement to 30, 70, and 100% led to 23, 23, and 25% lower f_{sp} relative to that of the control mix. This adverse effect of RCA is similar to that described earlier for f'_c . However, similar replacement percentages resulted in decreases in f'_c of 5, 5, and 21%, respectively. This signifies that f_{sp} was more influenced by the partial replacement of RCA replacement than f'_c . Figure 11 also presents the effect of steel fiber addition on the splitting tensile strength. Compared to those of the plain concrete mixes, f_{sp} increased by, on average, 98 and 193%, when 1 and 2% steel fibers were added, by volume, respectively, with values reaching up to 7.4 MPa. Similar enhancements in f_{sp} were noted in other work that incorporated steel fibers in NA-based alkali-activated concrete [83,84,94]. This shows that the adverse effect of RCA cannot only be countered by steel fiber addition but can also surpass that of the control mix made with NA (3.0 MPa), owing to the fibers' bridging effect and ability to increase the energy required for crack propagation. Furthermore, while the positive effect of steel fibers on f_{sp} was analogous to that on f'_c , the extent of improvement on f_{sp} was superior. Indeed, the ratio of f_{sp} -to- f'_c increased with steel fiber addition, indicating that steel fibers were more influential on f_{sp} than f'_c . In conclusion, alkali-activated slag concrete made with 30, 70, and 100% RCA can be produced with equivalent f_{sp} to that of the control provided that 1% steel fiber, by volume, is incorporated into the mix.

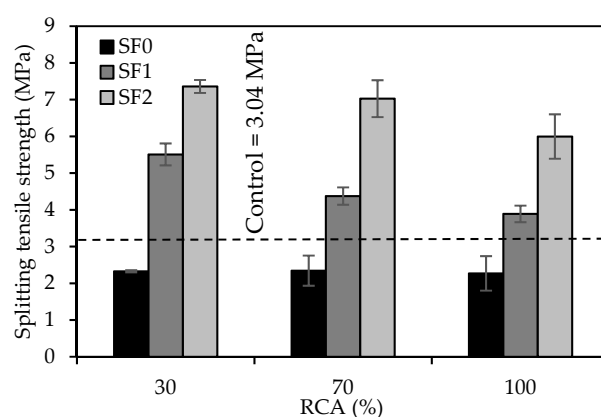


Figure 11. Splitting tensile strength of 28-day alkali-activated slag concrete.

Codified equations are typically employed in predicting the splitting tensile strength of concrete. In turn, limited investigation has been made to correlate this mechanical property to others. In this work, a linear model was developed to relate f_{sp} to f'_c . It is illustrated in the scatter plot of Figure 12a and presented in the form of Equation (9). However, the low correlation coefficient, $R^2 = 0.50$, shows that it is challenging to predict f_{sp} from f'_c with high accuracy. As such, Equation (10) was proposed as a multivariable linear regression relationship that incorporates steel fiber volume fraction (SF) and RCA

replacement as additional parameters to enhance the accuracy ($R^2 = 0.97$) of predicting f_{sp} from the range of f'_c values reported herein.

$$f_{sp} = 4.76\sqrt{f'_c} - 22.12 \quad (9)$$

$$f_{sp} = 0.55\sqrt{f'_c} - 0.01RCA + 2.13SF \quad (10)$$

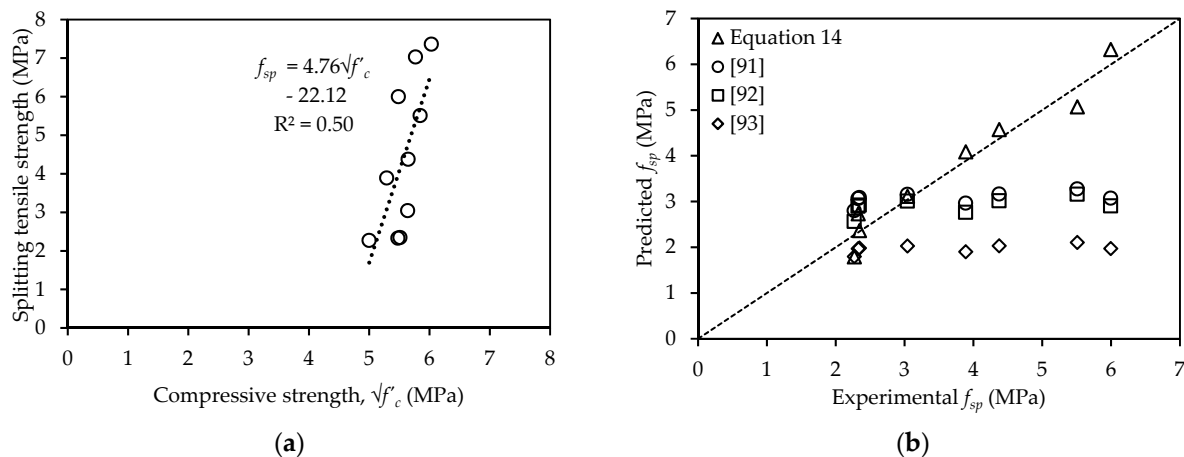


Figure 12. (a) Relationship between splitting tensile and cylinder compressive strength and (b) predicted versus experimental modulus of elasticity.

Figure 12b depicts the experimental versus predicted splitting tensile strength. In addition to Equation (10), codified equations of ACI 318, AS3600, and CEB-FIP [91–93] for plain conventional cement-based concrete were utilized to assess their feasibility to predict f_{sp} . It is clear that the codified equations can predict f_{sp} with reasonable accuracy for values ranging between 2 and 3 MPa, beyond which the accuracy was significantly reduced. This is because these equations do not account for the effect of steel fibers or RCA. As such, these equations cannot accurately predict f_{sp} for alkali-activated slag concrete made with RCA and steel fibers.

3.5. Water Absorption

The durability of concrete is affected by the concrete's resistance to penetration of damaging ions. Since water is the main carrier of these aggressive ions, the water absorption capacity of concrete can indicate its durability [54]. Figure 13 shows the water absorption of alkali-activated slag concrete at the age of 28 days. The control mix (R0F0) had a water absorption of 2.1%, while those of plain mixes incorporating 30, 70, and 100% RCA were 3.3, 5.8, and 7.5%, respectively. These represent 58, 173, and 255% increases over that of the control mix. In fact, every 10% RCA replacement led to, on average, a 23% increase in water absorption, owing to the porous nature of the RCA and the adhered mortar. This finding is well-correlated and provides evidence of the decrease in mechanical properties, including compressive strength, modulus of elasticity, and splitting tensile strength.

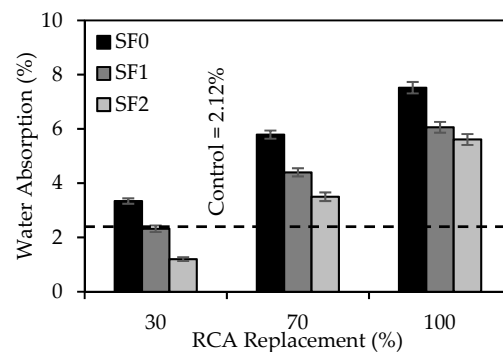


Figure 13. Water absorption of 28-day alkali-activated slag concrete.

Figure 13 also highlights the impact of steel fiber addition on the water absorption of alkali-activated slag concrete. Generally, an increase in steel fiber volume fraction led to a decrease in water absorption. In fact, it was reduced by, on average, 25 and 43% upon the incorporation of 1 and 2% steel fibers, by volume, compared to plain RCA counterparts. Accordingly, it can be concluded that steel fiber inclusion can densify the binding matrix, thereby reducing the water absorption and enhancing mechanical performance. Similar findings have been reported in alkali-activated slag concrete made with natural aggregates [94].

3.6. Capillary Sorptivity

Sorptivity represents the concrete's tendency to absorb and transport water into its microstructure through capillary action, making it an indirect tool to assess the durability of concrete. Indeed, it depends on the permeability and porosity of concrete as well as the strength of the capillary forces and the size and distribution of the pores [54,95]. Large capillary and small gel pores control the sorptivity. Because of the different sizes of these pores, two types of sorptivity are analyzed, namely initial and secondary sorptivity [96]. As the former pores are larger than the latter, water occupies them faster, causing initial sorptivity to be larger than secondary sorptivity. As such, the focus will only be on initial sorptivity.

Figure 14 presents typical plots of absorption over time and is used to find the rate of absorption or sorptivity of alkali-activated slag concrete. For plain mixes in Figure 14a, the slope of the sorptivity curve changes with time and is a function of RCA replacement. In fact, mixes made with 0, 30, 70, and 100% RCA maintained the same slope for up to 15, 90, 135, and 240 min (30, 73, 90, and 120 s^{0.5}), respectively, before the slope started to decrease. This shows that the higher the RCA replacement, the more water penetrates to fill the large pores present in the RCA, which may be cracks or fissures that develop during the production of RCA. In addition, RCA replacement was found to be proportional to the absorption at 360 min (147 s^{0.5}). Moreover, Figure 14b,c shows the sorptivity of mixes incorporating 1 and 2% steel fiber, by volume, respectively. Compared to the plain concrete mixes, the slope of the absorption curves did not significantly vary due to steel fiber incorporation, except for mixes made with 30% RCA, which underwent a significant decrease in the slope. In turn, the 360 min (147 s^{0.5}) absorption value experienced little to no change. Also, the slope changed at 3, 90, and 240 min (13, 73, and 120 s^{0.5}) for mixes made with 30, 70, and 100% RCA, respectively. As such, steel fiber-reinforced alkali-activated concrete mixes filled the larger pores faster than plain mixes due to steel fibers' ability to restrict water movement [97] and occupy void space in the alkali-activated slag structure. Other work reported similar findings in conventional cement-based steel fiber-reinforced concrete [97,98].

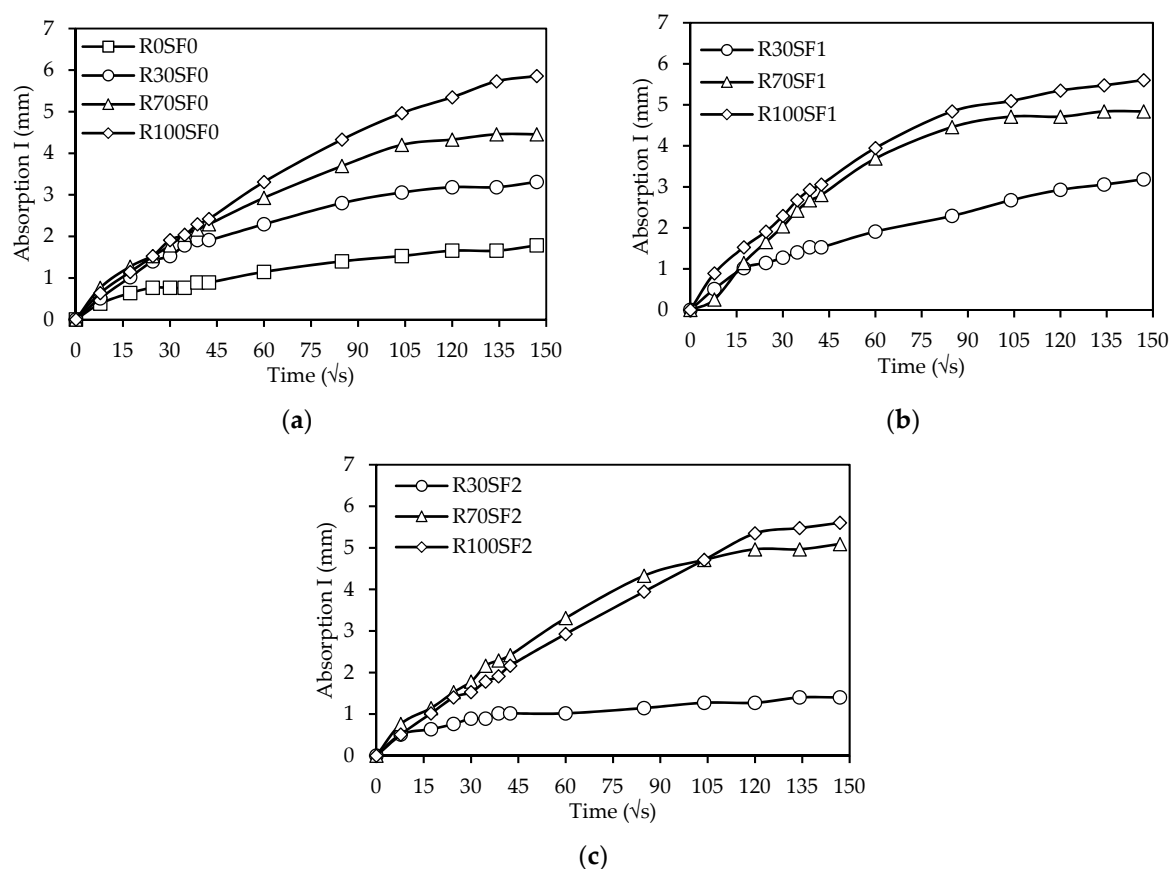


Figure 14. Capillary sorptivity of alkali-activated slag concrete over time: (a) SF 0%; (b) SF 1%; (c) SF 2%.

The sorptivity results of 28-day alkali-activated slag concrete mixes are summarized in Table 6. The replacement of NA by RCA increased the sorptivity. In plain mixes, 30, 70, and 100% RCA replacement led to 111, 256, and 356% higher sorptivity, respectively. Nevertheless, steel fiber incorporation decreased the sorptivity of RCA mixes. In fact, the addition of 1 and 2% steel fiber volume fractions reduced the sorptivity by, on average, 7.4 and 11.6%, respectively. Such a decrease with steel fiber inclusion may be due to the filling of the concrete voids [97,98] and/or an improvement in the bond within the binding matrix [99]. As such, it can be concluded that steel fiber inclusion can enhance alkali-activated slag concrete's resistance to water permeation and transport. Similar observations were reported in other work [50,97,98].

Table 6. Initial sorptivity of alkali-activated slag concrete mixes.

Mix No.	Mix Designation	RCA (%)	Steel Fibers (%)	Sorptivity $\times 10^{-2}$ (mm/ $\sqrt{s}$)
1	R0F0	0	0	0.86
2	R30F0	30	0	1.86
3	R30F1	30	1	1.70
4	R30F2	30	2	1.56
5	R70F0	70	0	3.15
6	R70F1	70	1	2.94
7	R70F2	70	2	2.85
8	R100F0	100	0	4.12
9	R100F1	100	1	3.96
10	R100F2	100	2	3.75

3.7. Ultrasonic Pulse Velocity and Bulk Resistivity

Concrete quality and durability can be indirectly assessed by the ultrasonic pulse velocity test. Figure 15a shows the results of alkali-activated slag concrete with RCA and steel fibers. Values ranged from 4.1 to 6.1 km/s. For plain concrete mixes, an increase in RCA from 0 to 30, 70, and 100% led to 5.6, 5.1, and 22.7% decreases in UPV, respectively. This is primarily due to the increase in voids and cracks with RCA replacement. As such, the corresponding mechanical properties were negatively impacted. Nevertheless, values of mixes R0F0, R30F0, and R70F0 were above 4.5 km/s, signifying excellent concrete quality based on IS 13311-1 [100]. The plain concrete mix made with 100% RCA was classified to have good quality with $v = 4.1$ km/s. Additionally, the effect of steel fiber incorporation on the UPV of alkali-activated slag concrete was evaluated. On average, the velocity increased by 7.7 and 15.8% when 1 and 2% steel fiber, by volume, were added. Such steel fiber-reinforced mixes were classified to have excellent concrete quality.

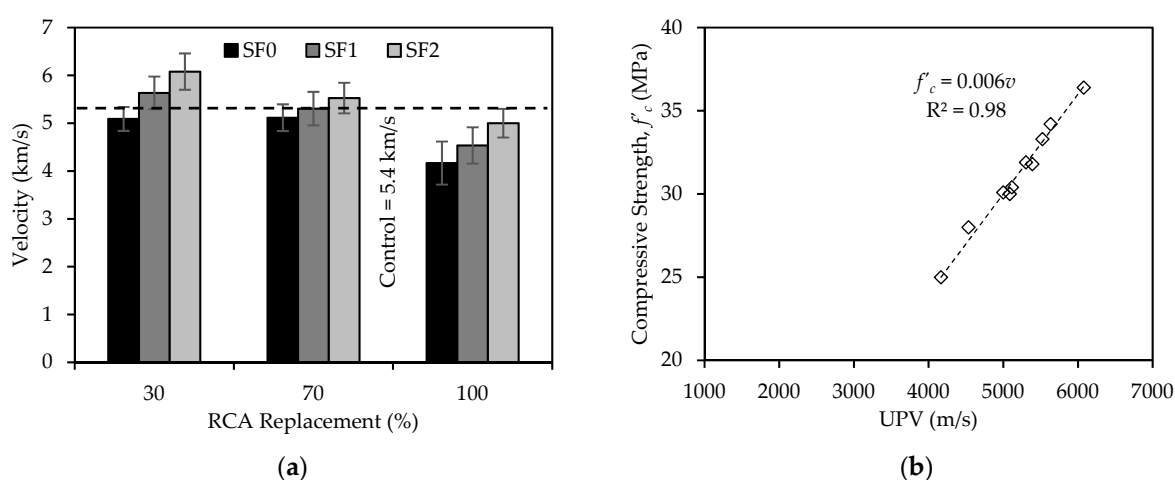


Figure 15. (a) Ultrasonic pulse velocity of alkali-activated slag concrete as a function of RCA replacement and (b) relationship between UPV and f'_c .

The UPV experimental test results were correlated to the 28-day cylinder compressive strength, f'_c , of this work. A strong linear equation (Equation (11)) is obtained from Figure 15b. With a high correlation coefficient, R^2 , of 0.98, it is possible to accurately predict the value of f'_c using the velocity, v , of a non-destructive test. Such an equation could be valuable to the construction industry to project the compressive strength of alkali-activated slag concrete made with RCA and steel fibers without conducting experimental destructive testing.

$$f'_c = 0.006v \quad (11)$$

Furthermore, concrete durability can be indirectly assessed using bulk electric resistivity or simply bulk resistivity. While 10 mixes were carried out in this work, those incorporating steel fibers were discarded. This is because steel fibers are electrically conductive, rendering the results incomparable and unrepresentative of true durability. Figure 16 presents the bulk resistivity results of alkali-activated slag concrete incorporating steel fibers and RCA. While the control mix with 0% RCA had a resistivity of 8.5 k Ω .cm, those of mixes incorporating 30, 70, and 100% RCA were 6.1, 5.5, and 4.9 k Ω .cm, respectively. This represents respective decreases of 28, 35, and 42% compared with the control mix, owing to the increase in pore space in the binder matrix. Also, while the replacement of NA by RCA adversely affected the bulk resistivity, the effect was not proportional to the RCA replacement percentage. In fact, 30% RCA replacement seemed to have lowered the bulk resistivity to the point that increasing the RCA replacement percentage did not cause further severe reduction.

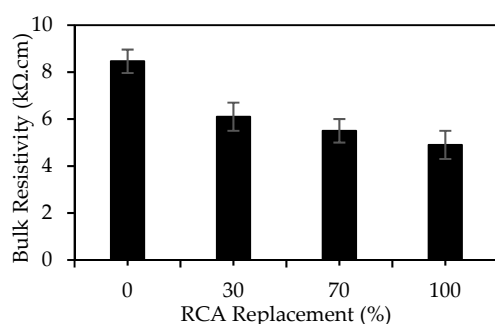


Figure 16. Bulk resistivity of alkali-activated slag concrete as a function of RCA replacement.

3.8. Abrasion Resistance

The mechanical properties of the concrete and the hardness of the aggregates govern its abrasion resistance. Figure 17 depicts the abrasion resistance of alkali-activated slag concrete, characterized by mass loss as a function of revolutions. For plain mixes made with RCA, the mass loss was mainly within the first 400 revolutions, while the control made with 0% RCA had a uniform mass loss over 500 revolutions. In fact, the control mix had a total abrasion mass loss of 33%, while mixes having 30, 70, and 100% NA replaced by RCA had total losses of 92, 97, and 100%, respectively. Such higher mass losses are associated with the inferior properties of RCA, as shown in Table 2, in addition to the weak interfacial bond between the old mortar and new paste. Similar findings were noted in conventional OPC concrete made with RCA [50,101]. Figure 17b,c show the abrasion mass loss of steel fiber-reinforced RCA alkali-activated slag concrete. The mass loss values for the mixes with steel fibers were much lower than those of their plain counterparts, indicating a much less pronounced influence of RCA on the abrasion resistance of the concrete upon inclusion of steel fibers.

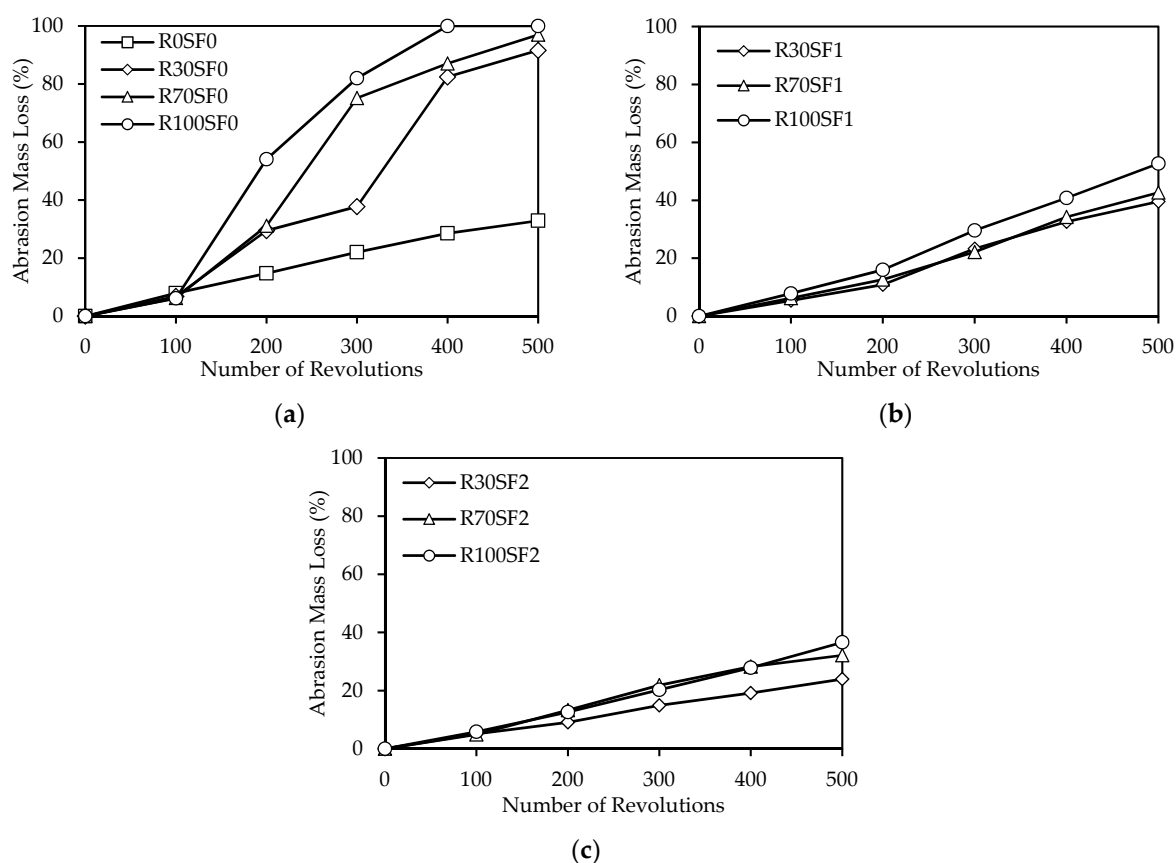


Figure 17. Abrasion resistance of alkali-activated slag concrete over time: (a) SF 0%; (b) SF 1%; (c) SF 2%.

From Figure 17, it can also be seen that the inclusion of 1 and 2% steel fiber decreased the abrasion mass loss by, on average, 53 and 68%, respectively. This is owed to the steel fibers' bridging effect and ability to improve the geometric integrity and densify the binding matrix, thereby increasing the abrasion resistance. Actually, all RCA-based mixes incorporating 2% steel fiber volume fraction had comparable abrasion resistance to that of the NA-based control mix.

4. Conclusions

In this paper, the feasibility of producing alkali-activated slag concrete for structural applications while utilizing recycled concrete aggregates and steel fibers was evaluated. The hardened properties of concrete made with up to 100% RCA and reinforced with up to 2% steel fibers, by volume, were examined. Based on the experimental test results, the following conclusive remarks can be made:

- The compressive strength development profile of the control mix showed that 81 and 98% of the 28-day cube compressive strength were attained within 1 and 7 days. Upon RCA replacement, the 1-, 7-, and 28-day cube compressive strengths were reduced by up to 44, 23, and 20%, respectively. However, this adverse effect of RCA replacement could be countered by steel fiber inclusion, with a more significant impact noted at 1 day.
- The effect of RCA replacement and steel fiber addition on the 28-day cylinder compressive strength (f'_c) is similar to that of the cube strength (f_{cu}). The confinement effect of cubes under compressive loads was unaffected by RCA replacement. As such, f'_c and f_{cu} of alkali-activated slag concrete were related using two linear regression models to predict one property from the other with reasonably to high accuracy ($R^2 = 0.85$ and 0.95). These relationships offer a more accurate approach in comparison with other models proposed in past literature.
- Plain alkali-activated slag concrete mixes achieved the design cylinder compressive strength of 30 MPa with 30 and 70% RCA replacement. The plain concrete mix made with 100% RCA replacement could not achieve design strength.
- An alkali-activated slag concrete mix could be produced with 100% RCA in combination with 2% steel fibers, by volume, while sustaining insignificant loss (<6%) in the 28-day cube and cylinder compressive strengths. Based on a comparison with data published in the literature, alkali-activated slag was found to be a more suitable binder than OPC in concrete made with more than 30% RCA.
- The replacement of NA by RCA decreased the peak stress and increased the corresponding peak strain of alkali-activated slag concrete. Steel fiber addition increased the peak stress and further increased the peak strain. This is indicative of enhanced deformability and energy absorption capacity.
- The slope of the compression stress-strain curves characterized the modulus of elasticity. The values of E_c decreased by up to 56% with 100% RCA replacement. The incorporation of steel fibers could enhance E_c by up to 43%. Yet, none of the mixes incorporating RCA and steel fibers could attain E_c of the control mix, highlighting a more pronounced impact of RCA replacement than steel fiber addition.
- The splitting tensile strength of alkali-activated slag concrete decreased with RCA replacement. Yet, every 1% steel fiber added led to, on average, a 97% increase in f_{sp} compared to plain counterparts, thus reversing the negative effect of RCA on f_{sp} . Also, RCA replacement and steel fiber addition had a more pronounced impact on f_{sp} than f'_c . All RCA-based mixes could be produced with equivalent or superior f_{sp} to that of the NA-based control when at least 1% steel fiber, by volume, was added.
- Two linear regression models were developed to estimate the E_c and f_{sp} . The prediction accuracy improved upon the inclusion of RCA replacement percentage and steel fiber volume fraction in the models. Codified equations could not provide accurate estimations of E_c and f_{sp} .

- The water absorption and sorptivity increased by up to 255 and 356%, respectively, upon replacing NA with RCA. Yet, it could be decreased by up to 65 and 16%, correspondingly, when steel fibers were added to the mixes. RCA replacement decreased the mechanical properties due to more pore space, i.e., higher water absorption and sorptivity, while steel fiber inclusion densified the binding matrix, i.e., less pore space, and improved the concrete's resistance to water permeation and transport, thereby enhancing its mechanical properties.
- The bulk resistivity and ultrasonic pulse velocity decreased by up to 42 and 23%, respectively, when NA was replaced by 100% RCA. Yet the plain mixes with 30 and 70% RCA were reported to have excellent concrete quality, while those made with 100% RCA were classified to have good concrete quality. The incorporation of steel fiber increased the UPV, resulting in excellent concrete quality for all RCA-based mixes. A linear regression model was proposed to predict UPV from f'_c with high accuracy ($R^2 = 0.98$).
- Abrasion mass loss increased with RCA replacement. The addition of steel fibers improved the resistance, i.e., reduced the mass loss, by up to 74%. Mixes incorporating 2% steel fiber, by volume, regardless of RCA replacement, had comparable abrasion resistance to that of the NA-based control mix.

Outcomes of the study revealed that it is feasible to produce alkali-activated slag concrete made with 100% RCA, steel fibers, and desert dune sand with hardened properties comparable to those of NA-based alkali-activated slag concrete, thus promoting its use in structural applications. Indeed, the research findings are considered a stepping stone toward the development of design recommendations for cement-free RCA-based concrete with steel fibers. Future studies will focus on the flexural properties and microstructure of steel fiber-reinforced RCA alkali-activated slag concrete mixes.

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