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Mechanical and durability properties of steel fiber-reinforced concrete containing coarse recycled concrete aggregate

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Abstract

The focus of this study is to investigate the effect of using coarse recycled concrete aggregates (RCAs) as an alternative material to natural coarse aggregate on the fresh, mechanical and durability behavior of concrete reinforced with steel fiber. Eighteen unique concrete mixes with RCA content of 0%, 50%, and 100% and steel fiber content of 0%, 1%, and 2% were prepared, and tests were performed to study slump, density, compressive and splitting tensile strengths, flexural behavior, surface hardness, surface abrasion resistance, water absorption, and sorptivity of each mix. It is shown that concrete containing RCA has a lower unit weight, compressive, splitting tensile and flexural strength, flexural toughness, surface hardness, and abrasion resistance, and a higher water absorption and sorptivity in comparison with conventional concrete. An increased compressive, splitting tensile and flexural strength, flexural toughness, surface hardness, and abrasion resistance, and a decreased water absorption and sorptivity of concrete with an increased steel fiber content from 1% to 2% is less significant compared to those from 0% to 1%. The results also show that, at RCA content of 50%, incorporating 1% steel fiber develops a concrete mix with similar or even better properties compared to unreinforced conventional concrete. At 100% RCA content, incorporating 2% steel fiber develops a concrete mix with similar properties to unreinforced conventional concrete having water to cement ratio of 0.3, but inferior properties to unreinforced conventional concrete having water to cement ratio of 0.5. These findings indicate that recycled aggregate concrete with similar or even better properties compared to concrete with natural aggregate can be developed through properly designing

Abbreviations: *c*, cement; C&D, construction and demolition waste; CMOD, crack mouth opening displacement; HSC, high strength concrete; ITZ, interfacial transition zone; NCA, natural coarse aggregate; NSC, normal strength concrete; *RA*, recycled aggregate volume replacement ratio; RCA, recycled concrete aggregate; SP, superplasticizer; SSD, saturated surface-dry; V_f, steel fiber volume fraction; *w*, water.

Discussion on this paper must be submitted within two months of the print publication. The discussion will then be published in print, along with the authors' closure, if any, approximately nine months after the print publication.

mixes, providing a great avenue toward the production of green construction material for structural applications.

KEYWORDS

coarse recycled concrete aggregate (RCA), durability, flexural toughness, steel fiber, strength

1 | INTRODUCTION

As the most widely used construction material in the world, concrete production is responsible for about 5%–7% of total carbon dioxide emission[1] and consumption of large amount of energy associated with extraction of natural aggregates.[2] As was reported by Pierrehumbert,[3] the emission of carbon dioxide into the atmosphere by cement production needs to be zero to stop global warming. In addition, over exploitation of natural aggregates for using in concrete production causes depletion of this non-renewable natural resource, resulting in significant environmental issues.[4] The use of coarse recycled concrete aggregate (RCA) in concrete production has received significant research attention in recent years.[5] As was reported previously, more than 17, 123, 850 and 15,000 Mt of construction and demolition waste (C&D) is produced per annum in Australia, USA, Europe and China,[6,7] respectively, but only 10% of them are being recycled.[7] Replacing natural aggregates with RCAs not only prevents the over-exploitation and depletion of non-renewable natural resources, but also reduces the environmental influence of disposal of C&D waste in landfill.[8,9]

Many studies were conducted on the behavior of concretes containing RCA (e.g., References 10–17). As was mentioned in literature, mechanical strength and durability characteristics of concretes having RCA were generally inferior in comparison with those without RCA.[18,19] This is attributed to the poor quality of RCAs owing to the porous nature of the attached mortar, resulting in their lower mechanical strength and durability-related properties.[20] It was shown that replacing natural coarse aggregates with RCA at 25%–50% replacement level had little or no influence on the workability and mechanical strength.[21–23] At replacement levels of higher than 50%, the mechanical characteristics of concrete prepared with RCA were significantly lower in comparison with those prepared with natural aggregate.[24,25] Therefore, using RCA at high replacement levels was limited to non-structural applications in the construction industry.[26]

It is now well-known that incorporating steel fibers leads to an enhanced mechanical performance of concrete by improving crack propagation, ductility, and toughness of concrete.[27–30] Steel fiber can also reduce the general ecological effect of construction because of an improved maintenance life of structures manufactured with steel fiber-reinforced concrete.[31,32] There is limited knowledge on characteristics of steel fiber-reinforced concrete containing RCA. Carneiro et al.[33] and Guo et al.[34] showed that incorporating steel fibers improved the fracture toughness of concrete produced with RCA. Gao and Zhang[35] reported that adding steel fiber to concrete containing RCA had a more significant impact on the flexural strength compared to the compressive strength. Erdem et al.[36] showed through microstructural analysis that steel fiber could reduce inherent microcracks development in concrete having RCA. Afroughsabet et al.[37] found that adding steel fiber caused a decreased water absorption and drying shrinkage in concrete containing RCA. They observed that concrete produced with 100% RCA and 1% steel fiber had only slightly more absorption than unreinforced natural aggregate concrete.[37] Mohseni et al.[38] found that, for a given fiber content, concrete containing RCA reinforced with steel fiber exhibited a higher compressive and tensile strength and lower absorption compared to that reinforced with polypropylene fiber. Xie et al.[39] presented that enhancement of flexural strength and toughness of recycled aggregate concrete incorporating steel fiber was better than those incorporating polypropylene fiber. Ibrahim et al.[29] reported that using steel fiber by 0.5%, 1%, and 1.5% improved the shear strength of concrete containing 70% RCA by 24.5%, 40.6%, and 59.4%, respectively.

Based on the above literature review, the existing studies illustrated the great potential of improving the properties of concrete containing RCAs through incorporating steel fibers. However, previous studies focused on mechanical performance of steel fiber-reinforced concretes containing RCA and very limited studies investigated their durability properties. The focus of this study is to investigate the mechanical and durability performance of steel fiber-reinforced concrete containing RCA. Testing program is initially presented, which is followed by the experimental test results and discussions. A number of tests were performed on the concretes to assess their performance, including slump, density, compressive strength, splitting tensile strength, flexural behavior, surface hardness, surface abrasion, water absorption, and sorptivity.

2 | RESEARCH SIGNIFICANCE

This study focuses on the mechanical and durability properties of steel fiber-reinforced concrete containing RCA. The results of this research significantly point to the great perspective of manufacturing recycled aggregate concrete using steel fiber reinforcement with a similar or even better mechanical and durability properties in comparison with unreinforced natural aggregate concrete, causing a decreased impact of disposal of C&D waste on environment and depletion of natural resources.

3 | TESTING PROGRAM

3.1 | Materials

Portland cement with chemical composition shown in Table 1 was used as binder in this study. Natural river sand (shown in Figure 1) with 0–5 mm was utilized as fine aggregate and limestone (shown in Figure 1) with particle sizes of 5–22 mm was utilized as natural coarse aggregate. RCA shown in Figure 1 with particle sizes of 5–22 mm was used as the replacement material for the natural coarse aggregate. RCAs were obtained from building debris in Kastamonu, Turkey. Old concretes separated from reinforced concrete structural elements were crushed in the laboratory by a jaw crusher. Table 2 and Figure 2 present the physical properties and particle size distribution of sand and coarse aggregates, respectively. Hooked-end steel fibers, which is shown in Figure 1, were used with 60 mm length and 0.9 mm diameter. Table 3 represents characteristics of steel fibers. Polycarboxylate ether-based superplasticizer was used in this study as the water reducing admixture.

3.2 | Specimens and testing

Eighteen unique mixes of concrete were manufactured, including nine normal strength concrete (NSC) and nine high strength concrete (HSC). The control mix of NSC group was designed to have 30 MPa compressive strength and control mix of HSC group was aimed to have 60 MPa compressive strength. The water to cement (w/c) ratio in NSC and HSC groups was set as 0.5 and 0.3 to develop workable concrete mixes, respectively. Steel fibers were introduced into mixes at 1% and 2% fiber volume fractions (V_f). These fiber volume fractions were selected based on literature review (e.g., References 40–43), considering that the fiber volume fraction does not affect the mechanical properties of concrete negatively. Natural coarse aggregates were replaced with RCAs at two volume replacement levels (RA) of 50% and 100%. Table 4 shows the mixture proportions of different concrete mixes.

To remove impurities of RCAs, they were washed and then kept to dry in oven at $100 \pm 5°C$ for 24 h. They were finally cooled for about 3 h at ambient temperature before using in the concrete production. After demolding the concrete specimens, they were kept in fog room with $23 \pm 2°C$ till testing day according to ASTM C192 standard.[44]

Different tests were conducted on each mix to assess the performance of the concretes, including workability, fresh unit weight, compressive strength, splitting tensile strength, bending, Schmidt hardness, abrasion, water absorption, and sorptivity tests. Figure 3(a)–(f) show the photo of compression, splitting tension, bending, Schmidt hardness, abrasion, and sorptivity tests, respectively. Workability test was done according to ASTM C143 standard[45] and test of unit weight was done according to ASTM C138 standard[46] on the fresh mixtures. For compression and splitting tension tests, Ø150 × 300 mm cylinder samples were prepared and tested based on the ASTM C39[47] and ASTM C496[48] codes, respectively. Three-point bending test was conducted on prisms with dimension of 150 × 150 × 600 mm for measuring the flexural properties of the mixes based on BS EN 14651.[49] In the bending test, 25-mm deep and 2-mm wide notch was created at the mid-span of the prisms. For measuring the crack mouth opening displacement (CMOD) of specimens in bending test, two clip gauges at notch center were mounted. Schmidt hammer test was done on 150 mm cubes for measuring the surface hardness of the concrete specimens by recording 10 readings from each

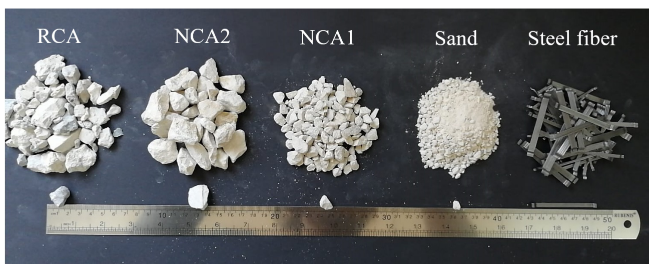

FIGURE 1 Sand, coarse aggregates, and steel fiber

TABLE 1 Chemical composition of cement (%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
22.77	5.83	2.97	60.30	2.51	0.13	0.80	3.00

TABLE 2 Properties of sand and coarse aggregates

Aggregate type	Maximum size (mm)	Specific gravity (SSD)	Water absorption (%)	Fineness modulus
Sand	5	2.68	1.14	2.70
Natural coarse aggregate-1 (NCA-1)	22	2.70	0.79	2.20
Natural coarse aggregate-2 (NCA-2)	11	2.71	0.60	3.05
Recycled concrete aggregate (RCA)	22	2.43	6.14	2.48

Abbreviation: SSD, saturated surface dry.

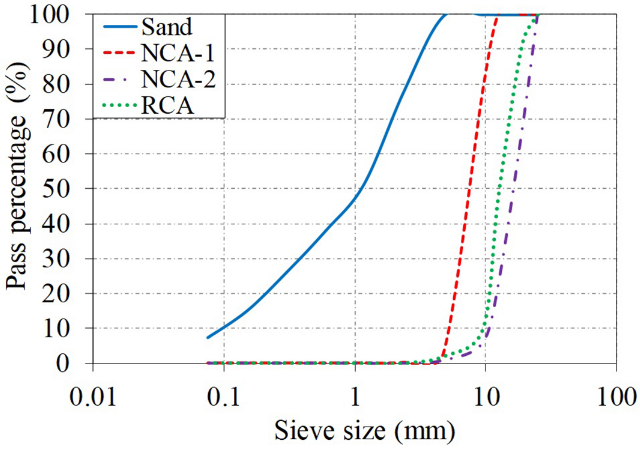

FIGURE 2 Sieving test results of sand and coarse aggregates: Particle size distribution

test area, according to ASTM C805 standard.[50] Abrasion test was done on the cubes with 150 mm dimension using a rotary cutter device to obtain the surface abrasion resistance of the concretes according to ASTM C944.[51] The device was set to rotate at the speed of 200 rpm for 2 min with the vertical load of 98 N. Water absorption test was performed according to ASTM C642[52] on concrete cylinders with the size of 75 × 150 mm. Finally, sorptivity test was done on 100 mm cubes to investigate the rate of water absorption and capillary suction in accordance with ASTM C1585.[53] Compressive and splitting tensile strength, Schmidt hardness and surface abrasion experiments were fulfilled at 7 and 28 days of curing, bending and water absorption tests were performed at 28 days of curing, and sorptivity test was performed until 28 days of curing. Presented test results in this study were based on the average values of three nominally similar specimens.

3.3 | Designation of concrete specimens

Concrete specimens were labeled as follows in this study: the letters R0, R50, and R100 mean the concrete

TABLE 3 Material properties of steel fibers

Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	Young modulus (GPa)
60	0.9	67	1160	210

specimens with 0%, 50%, and 100% RCA, respectively. The letters F0, F1, and F2 indicate the specimens containing 0%, 1%, and 2% steel fibers, respectively. Finally, the letters A and B stand for the concrete specimens with *w/c* of 0.3 and 0.5, respectively. As an example, R50F2B is a concrete specimen with *RA* of 50%, V_f of 2% and *w/c* of 0.5.

4 | RESULTS AND DISCUSSIONS

4.1 | Workability and density of fresh concretes

The workability (slump) test results are presented in Table 4. As can be seen from Table 4, the superplasticizer was added to the mixtures to keep the slump almost constant with an increase in V_f and *RA*.

Figure 4(a),(b) show the unit weight of mixes with 0.3 and 0.5 *w/c*, respectively. As can be observed in the figures, at a given V_f and *RA*, the mixtures with 0.3 *w/c* exhibited 5%–7% higher unit weight compared to those with *w/c* of 0.5. This observation agrees with previous studies on conventional concrete[54,55] and self-compacting concrete.[56,57] It is also shown in the figures that, at a given *w/c* and *RA*, incorporating 1% and 2% steel fiber led to approximately 3% and 5% increase in the unit weight of concrete, respectively. As seen from Figure 4(a),(b), replacing natural coarse aggregates with RCAs caused a decreased unit weight and an increased RCA replacement level caused a decrease in the unit weight. This is because of less specific gravity of RCA compared to that of natural coarse aggregate, which was shown in Table 2. Mixes containing 50% and 100% RCA experienced

TABLE 4 Mixture proportions of different mixes

Mix	V_f (%)	*RA* (%)	Cement (kg/m³)	Water (kg/m³)	w/c	Sand (kg/m³)	Natural coarse aggregate-1 (kg/m³)	Natural coarse aggregate-2 (kg/m³)	Recycled concrete aggregate (kg/m³)	Steel fiber (kg/m³)	SP (kg/m³)	Slump (mm)
R0F0A	0	0	400	120	0.3	938	352	664	0	0	3	155
R0F1A	1	0	400	120	0.3	935	351	662	0	30	5	155
R0F2A	2	0	400	120	0.3	936	351	663	0	45	7	160
R50F0A	0	50	400	120	0.3	926	173.5	328	501.5	0	3	150
R50F1A	1	50	400	120	0.3	924	173.5	327.5	501	30	4	150
R50F2A	2	50	400	120	0.3	923	172	327	499	45	4.5	150
R100F0A	0	100	400	120	0.3	906	0	0	982	0	4	145
R100F1A	1	100	400	120	0.3	905	0	0	980	30	5	145
R100F2A	2	100	400	120	0.3	903	0	0	979	45	5	140
R0F0B	0	0	400	200	0.5	837	314	593	0	0	0	170
R0F1B	1	0	400	200	0.5	836	314	592	0	30	0	160
R0F2B	2	0	400	200	0.5	836	313	592	0	45	0.5	160
R50F0B	0	50	400	200	0.5	821	154	290.5	444.5	0	0	165
R50F1B	1	50	400	200	0.5	820	154	290.5	444.5	30	0.5	160
R50F2B	2	50	400	200	0.5	819	153.5	290	443.5	45	1	160
R100F0B	0	100	400	200	0.5	803	0	0	870	0	0	160
R100F1B	1	100	400	200	0.5	802	0	0	869	30	0.5	155
R100F2B	2	100	400	200	0.5	802	0	0	869	45	1	155

Abbreviation: SP, superplasticizer.

approximately 3% and 7% lower unit weight in comparison with those without RCA, respectively.

4.2 | Compressive strength

Figure 5(a),(b) represent compressive strengths of mixes of 0.3 and 0.5 *w/c*, respectively. As shown in the figures, at a given curing age, mixes of 0.3 *w/c* had a higher compressive strength in comparison to those with *w/c* of 0.5 for a given V_f and *RA*. This observation was explained by the decreased free water among particles of concrete with decreased *w/c*, resulting in less porous microstructure and increased concrete strength.[56,58] It is also shown in the figures that, at a given curing age, *w/c* , and *RA*, incorporating steel fiber caused increase of the compressive strength, and the strength improvements were more significant in concretes containing a higher RCA content. At *w/c* of 0.3, R0, R50, and R100 mixes containing 1% steel fiber had 23%, 25%, and 29% higher 7-day compressive strength and 14%, 21%, and 31% higher 28-day compressive strength in comparison with those companion mixes without steel fiber, respectively. At *w/c* of 0.5, R0, R50, and R100 mixes containing 1% steel fiber experienced 12%, 15%, and 17% higher 7-day compressive strength and 12%, 13%, and 15% higher 28-day compressive strength in comparison with those companion mixes without steel fiber, respectively. It can be observed that increasing V_f from 1% to 2% caused slight improvement of compressive strength. At 0.3 *w/c*, R0, R50, and R100 mixes containing 2% steel fiber had 8%,

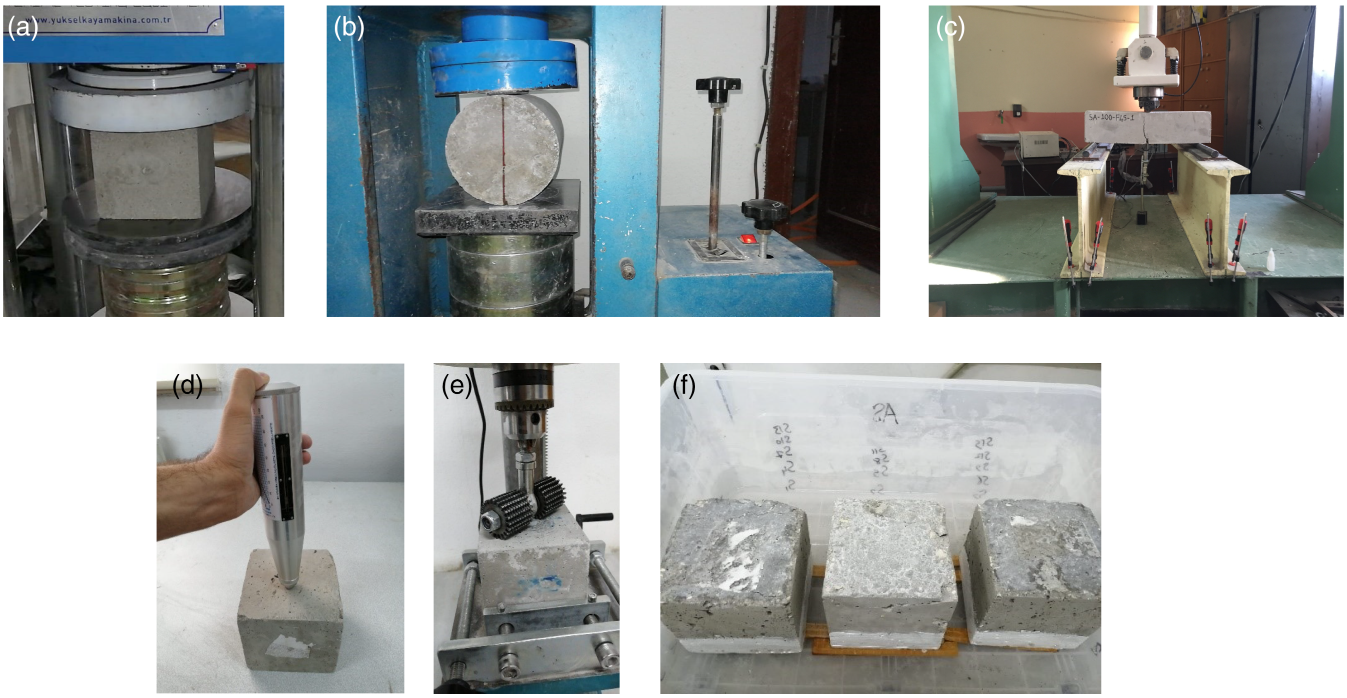

FIGURE 3 Photo of (a) compression, (b) splitting tension, (c) bending, (d) Schmidt hardness, (e) abrasion, and (f) sorptivity tests

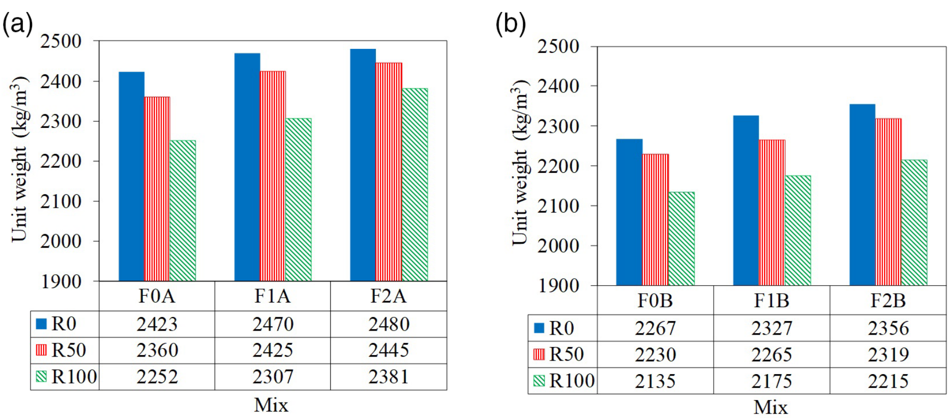

FIGURE 4 Unit weight of different mixes: (a) $w/c = 0.3$ and (b) $w/c = 0.5$

11%, and 13% higher 7-day compressive strength and 5%, 6%, and 7% higher 28-day compressive strength in comparison with those companion mixes containing 1% steel fiber, respectively. At *w/c* of 0.5, R0, R50, and R100 mixes containing 2% steel fiber had 7%, 8%, and 9% higher 7-day compressive strength and 5%, 6%, and 13% higher 28-day compressive strength in comparison with those companion mixes containing 1% steel fiber, respectively. The higher strength of mixes containing steel fiber compared to the unreinforced mixes is owing to the arresting behavior of fibers in creation and propagation of microcracks through bonding between the fibers and paste matrix.[59] The less significant strength enhancements of the concrete from 1% to 2% steel fiber compared to those from 0% to 1% steel fiber agree with previous studies on conventional concrete.[59–62] As was reported previously,[63] this observation can be owing to the less uniform dispersion of steel fibers in concrete mix with V_f of 2% compared to that with V_f of 1%.

As can be observed in Figure 5(a),(b), at a given *w/c*, curing age, and V_f, concrete mixes containing RCAs exhibited a lower strength than those without RCA. At *w/c* of 0.3, F0, F1, and F2 mixes containing 50% RCA developed 13%, 11%, and 9% lower 7-day compressive strength and 11%, 6%, and 6% lower 28-day strength in comparison with those companion mixes without RCA, respectively. At 0.5 *w/c*, F0, F1, and F2 mixes containing 50% RCA developed 12%, 10%, and 9% lower 7-day strength and 13%, 12%, and 11% lower 28-day strength in comparison with those companion mixes without RCA, respectively. It is also shown that an increased *RA* led to a decreased strength. At 0.3 *w/c*, mixes produced with 100% RCA developed 20%–24% and 15%–23% lower 7- and 28-day compressive strength compared to those containing 50% RCA, respectively. At *w/c* of 0.5, mixes containing 100% RCA experienced 45% and 31%–36% lower 7- and 28-day compressive strength compared to those containing 50% RCA, respectively. Less strength of mixes containing RCA compared to those without RCA agrees with previous studies on unreinforced concrete[64,65] and is related to the existence of weak interfacial transition zones (ITZs) in the microstructure of concrete having RCA between (i) aggregate and old mortar attached to RCA and (ii) new mortar and old mortar.[66]

By comparison between the compressive strength of different mixes presented in Figure 5(a),(b), it can be observed that when 50% of natural coarse aggregates in unreinforced concrete were replaced with RCAs, compressive strength of the concrete decreased by 11%–13%. However, adding 1% steel fiber could develop a mix with a higher compressive strength in HSC mixes and a

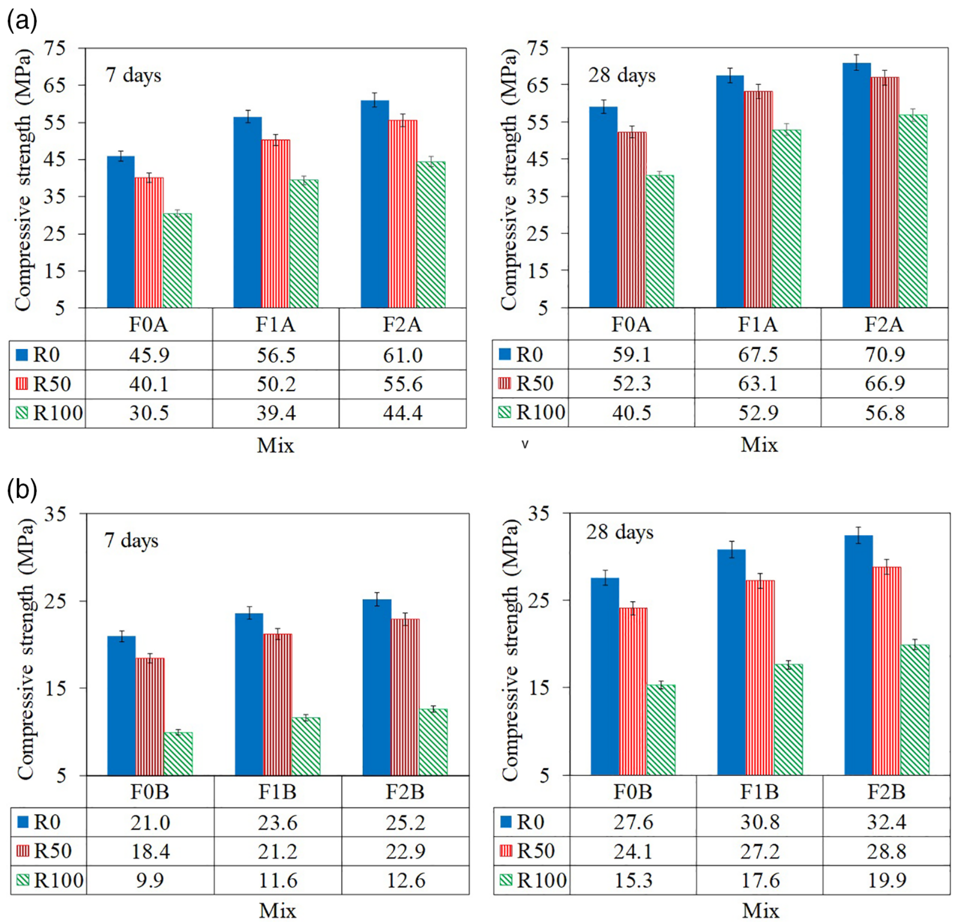

FIGURE 5 Compressive strengths of different mixes at 7 and 28 days: (a) $w/c = 0.3$ and (b) $w/c = 0.5$

similar compressive strength in NSC mixes compared to companion unreinforced natural aggregate concrete. In addition, complete substitution of natural coarse aggregates with RCA in unreinforced concrete mixes caused 31%–53% reduction in compressive strength. In NSC mix with 100% RCA, incorporating steel fiber even at 2% V_f developed a lower strength in comparison with companion unreinforced concrete mix. In HSC mixes, incorporating 1% steel fiber developed a lower compressive strength, but incorporating 2% steel fiber could develop a nearly similar compressive strength compared to the companion unreinforced natural aggregate concrete. These results indicate that designing mixes properly with steel fiber can compensate the strength reduction of the concrete causing by the replacement of natural coarse aggregate with RCA even at 100% replacement level.

4.3 | Splitting tensile strength

Figure 6(a),(b) illustrate splitting tensile strengths of concrete mixes with 0.3 and 0.5 *w/c*, respectively. At a given curing age, mixes with 0.3 *w/c* developed a higher splitting tensile strength in comparison with those with *w/c* of 0.5 for a given V_f and *RA*. This behavior is consistent with previous studies on steel fiber-reinforced concrete,[67–69] recycled aggregate concrete[12] and self-compacting concrete.[70] As can also be observed in the figures, for a given curing age, *w/c*, and *RA*, incorporation of steel fibers caused an increased splitting tensile strength. At 0.3 *w/c*, R0, R50, and R100 mixes containing 1% steel fiber exhibited 23%, 25%, and 27% higher 7-day splitting tensile strength and 22%, 25%, and 25% higher 28-day splitting tensile strength in comparison with companion unreinforced mixes, respectively. At 0.5 *w/c*, R0, R50, and R100 mixes containing 1% steel fiber exhibited 13%, 20%, and 75% higher 7-day splitting tensile strength and 21%, 28%, and 38% higher 28-day splitting tensile strength than companion unreinforced mixes, respectively. The higher splitting tensile strength of mixes having steel fiber compared to that of the unreinforced mixes is owing to the bridging influence of steel fibers on the microstructure of concrete.[71] As illustrated in the figures, an increased V_f from 1% to 2% caused a slight improvement of splitting tensile strength. This observation agrees with previous studies on conventional concrete[37,61,63,68] and self-compacting concrete.[71] At *w/c* of 0.3, R0, R50, and R100 mixes containing 2% steel fiber experienced approximately 11% higher 7- and 28-day splitting tensile strength compared to companion mixes containing 1% steel fiber. At *w/c* of 0.5, R0, R50,

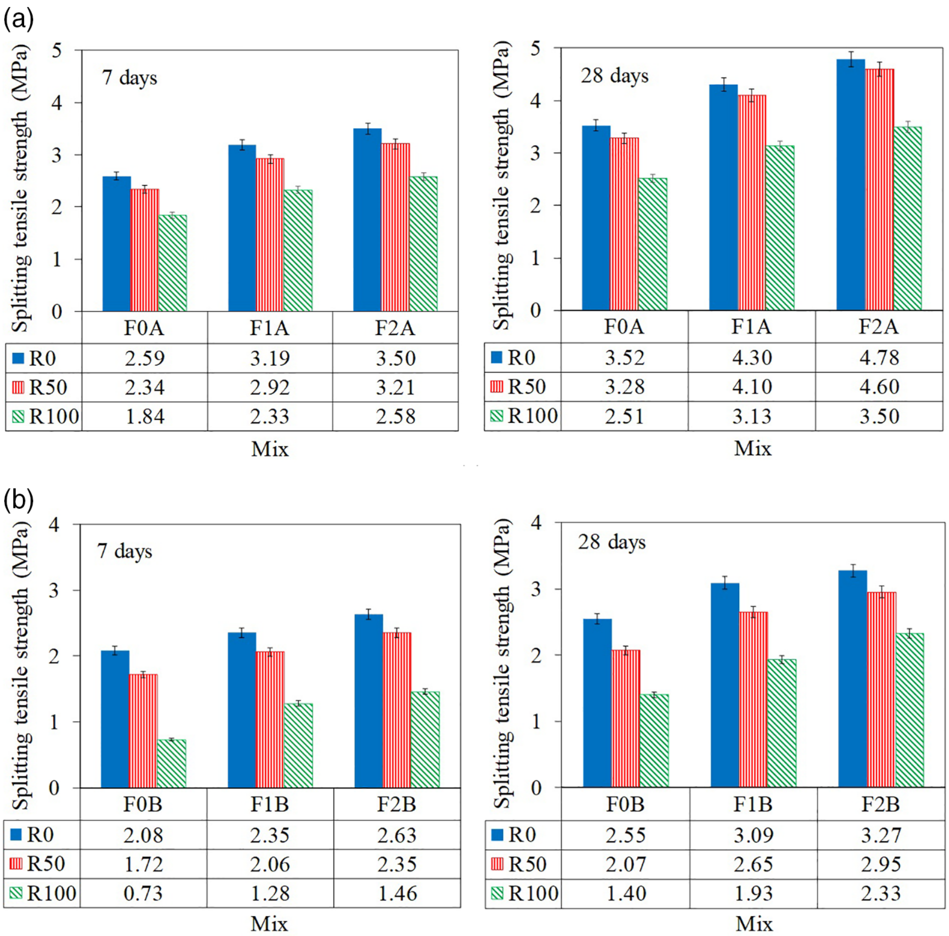

FIGURE 6 Splitting tensile strength of different mixes at 7 and 28 days: (a) $w/c = 0.3$ and (b) $w/c = 0.5$

and R100 mixes containing 2% steel fiber experienced 12%, 14%, and 14% higher 7-day splitting tensile strength and 6%, 11%, and 21% higher 28-day splitting tensile strength than companion mixes containing 1% steel fiber, respectively.

It is shown in Figure 6(a),(b) that, for a given *w/c*, curing age and V_f, replacing natural coarse aggregates with RCA led to a decreased splitting tensile strength. At *w/c* of 0.3, mixes containing 50% RCA exhibited 8%–10% lower 7-day and 4%–7% lower 28-day splitting tensile strength, and at *w/c* of 0.5, mixes containing 50% RCA had 11%–17% lower 7-day and 10%–19% lower 28-day splitting tensile strength compared to companion mixes without RCA. As also shown in the figures, the splitting tensile strength decreased with increasing of *RA*. At 0.3 *w/c*, mixes with 100% RCA experienced approximately 21% lower 7-day and 24% lower 28-day splitting tensile strength, and at 0.5 *w/c*, mixes with 100% RCA experienced 38%–58% lower 7-day and 21%–32% lower 28-day splitting tensile strength compared to companion mixes having 50% RCA. Lower splitting tensile strength of the concrete mixes having RCA aggregates compared to those without RCA is consistent with previous studies on unreinforced conventional concrete[64] and self-compacting concrete[12,57,72] and is because of the decreased tensile strength of the aggregate-mortar ITZ when natural coarse aggregates are replaced with RCAs.[66]

Similar to the trends observed in compressive strength test results, splitting tensile strength of the concretes containing 50% RCA and 1% steel fiber was higher in comparison with that of the unreinforced concrete without RCA. Furthermore, NSC mixes containing 100% RCA developed a lower splitting tensile strength at 1% and 2% steel fiber compared to companion mixes without RCA, but HSC mixes containing 100% RCA experienced a similar splitting tensile strength to the companion mixes without RCA when 2% steel fiber was incorporated.

Table 5 shows the comparison between the splitting tensile strengths of this study and predictions obtained from existing models. It can be seen in the table that the model by Oluokun[75] exhibited the most accurate predictions of the splitting tensile strength of specimens with *w/c* of 0.3, which was followed by ACI 318-11,[73] CEB-FIP,[74] Choi and Yuan,[77] and Ramadoss and Nagamani[76] models, respectively. It can also be observed that the model by CEB-FIP[74] showed the most accurate predictions of the splitting tensile strength of specimens with *w/c* of 0.5, followed by ACI 318-11,[73] Oluokun,[75] Ramadoss and Nagamani,[76] and Choi and Yuan[77] models, respectively.

4.4 | Flexural behavior

Figure 7(a),(b) show load-CMOD curves of steel fiber-reinforced concrete mixes with 0.3 and 0.5 *w/c* at 28 days, respectively. It is shown in the figures that the concrete mixes had a noticeable load drop after peak load. Mixes with a higher RCA content had a larger load drop after peak load compared to those with a lower RCA content, and the load drop was less pronounced in mixes with 2% steel fiber than those with 1% steel fiber. The larger load drops of mixes with a higher *RA* can be because of the low strength quality of RCAs, and the smaller load drop of mixes with a higher V_f can be because steel fibers could be able to pick up the load by their crack bridging mechanism.[78] The tooth-shape curve after peak load indicates the gradual pulling out of steel fibers from the paste matrix.[62] As can be observed in the figures, for a given *w/c* and *RA*, an increased V_f caused an increased residual flexural load of concrete. It is also shown that, for a given *w/c* and V_f, incorporating RCA led to a decreased residual load and an increased *RA* caused a decrease in the residual load of the concrete.

Table 6 represents the flexural test results of different mixes at 28 days, including the load at the first crack, flexural tensile strength and residual flexural strength at CMODs of 0.5, 1.5, 2.5, and 3.5 mm. As the concretes without steel fibers failed before CMOD reached to 0.5 mm, the residual flexural strength for them was not applicable. As can be observed in the table, for a given V_f and *RA*, the first crack load in mixes with *w/c* of 0.3 was 32%–53% larger than those with *w/c* of 0.5. NSC and HSC mixes with 2% steel fiber developed approximately 4% and 5% higher first crack load compared to those companion mixes with 1% steel fiber for a given *RA*, respectively. The slight increase in the first crack load with an increased V_f indicates that the first crack stress is mainly controlled by the matrix rather than the fibers, which is consistent with previous studies on steel fiber-reinforced mortars.[62,71,79,80] It is also shown in the table that, for a given *w/c* and V_f, mixes with RCAs developed a lower first crack load (6%–10% for *RA* of 50%) compared to those without RCA, and an increased *RA* caused a decreased first crack load (6%–18% from *RA* of 50%–100%). This observation agrees with previous studies on concretes with longitudinal reinforcement.[81,82]

As shown in Table 6, for a given steel fiber and RCA content, concrete mixes with *w/c* of 0.3 developed higher flexural tensile and residual flexural strengths in comparison with those with *w/c* of 0.5. This agrees with the previous study on steel fiber-reinforced cement mortar.[83] It can be observed that incorporating steel fibers caused an increase in the flexural tensile strength for a given *w/c* and *RA*, and strength increases were more significant in HSC mixes than those in NSC mixes. An increased flexural strength with incorporating steel fiber is consistent with previous studies[43,84–86] and is owing to the reinforcement effect of fibers on controlling the crack propagation

TABLE 5 Comparison between experimental results of splitting tensile strength and predictions by existing models for fiber-reinforced concrete

	Experimental results		ACI 318–11[73]		CEB-FIP[74]		Oluokun[75]		Ramadoss and Nagamani[76]		Choi and Yuan[77]	
Mix	**f'_c (MPa)**	**f_{st} (MPa)**	**f_{st} (MPa) = 0.56 $(f'_c)^{0.5}$**	**Error (%)**	**f_{st} (MPa) = 0.3 $(f'_c)^{2/3}$**	**Error (%)**	**f_{st} (MPa) = 0.21 $(f'_c)^{0.55}$**	**Error (%)**	**f_{st} (MPa) = 0.485 $(f'_c)^{0.56}$**	**Error (%)**	**f_{st} (MPa) = 0.6$(f'_c)^{0.5}$**	**Error (%)**
R0F0A	59.1	3.52	4.31	−22.3	4.61	−31.1	3.65	−3.70	4.76	−35.3	4.61	−31.0
R0F1A	67.5	4.30	4.60	−7.00	5.04	−17.3	4.01	6.83	5.13	−19.3	4.93	−14.6
R0F2A	70.9	4.78	4.72	1.35	5.21	−9.05	4.15	13.3	5.27	−10.3	5.05	−5.69
R50F0A	52.3	3.28	4.05	−23.5	4.25	−29.6	3.35	−2.16	4.45	−35.6	4.34	−32.3
R50F1A	63.1	4.10	4.45	−8.50	4.82	−17.6	3.82	6.79	4.94	−20.5	4.77	−16.2
R50F2A	66.9	4.60	4.58	0.35	5.01	−9.07	3.98	13.4	5.10	−11.1	4.91	−6.76
R100F0A	40.5	2.51	3.56	−42.0	3.58	−42.7	2.80	−11.6	3.85	−53.5	3.82	−52.1
R100F1A	52.9	3.13	4.07	−30.1	4.28	−36.9	3.38	−7.92	4.48	−43.0	4.36	−39.4
R100F2A	56.9	3.50	4.22	−20.6	4.49	−28.4	3.55	−1.44	4.66	−33.1	4.52	−29.2
AAE (%)				**17.3**		**24.6**		**7.46**		**29.1**		**25.2**
R0F0B	27.6	2.55	2.94	−15.4	2.77	−8.64	2.14	16.0	3.11	−21.9	3.15	−23.6
R0F1B	30.8	3.09	3.11	−0.58	2.98	3.51	2.31	25.1	3.31	−7.00	3.33	−7.76
R0F2B	32.4	3.27	3.19	2.67	3.08	5.81	2.40	26.8	3.40	−3.86	3.42	−4.28
R50F0B	24.1	2.07	2.75	−32.8	2.53	−22.2	1.95	5.88	2.88	−39.2	2.95	−42.3
R50F1B	27.2	2.65	2.92	−10.2	2.74	−3.52	2.12	20.0	3.08	−16.4	3.13	−18.1
R50F2B	28.8	2.95	3.01	−1.87	2.85	3.37	2.21	25.2	3.18	−7.94	3.22	−9.15
R100F0B	15.3	1.40	2.19	−56.1	1.87	−33.0	1.42	−1.00	2.23	−59.2	2.35	−67.2
R100F1B	17.6	1.93	2.35	−21.5	2.05	−6.01	1.56	19.1	2.42	−25.0	2.52	−30.2
R100F2B	19.9	2.33	2.50	−7.22	2.23	4.50	1.70	26.9	2.59	−11.1	2.68	−14.9
AAE (%)				**16.5**		**10.1**		**18.4**		**21.3**		**24.2**

Note: f'_c, 28-day compressive strength; f_{st}, 28-day splitting tensile strength.
Abbreviation: AAE, average absolute error.

of the concrete.[71] After cracking in concretes, the applied load is sustained by mechanical interlocking and friction between fibers and paste matrix.[62] As HSC has a stronger paste matrix, more significant flexural strength increases were observed in HSC with incorporating steel fiber compared to those observed in NSC.[87] Mixes with 0.3 and 0.5 *w/c* containing 1% steel fiber experienced an approximately 66% and 50% higher flexural tensile strength compared to companion unreinforced mixes, respectively. Increasing V_f caused an increased flexural tensile and residual flexural strengths for a given *w/c* and *RA*. Mixes with 0.3 and 0.5 *w/c* containing 2% steel fiber developed an approximately 14% and 11% higher flexural tensile strength compared to those companion mixes containing 1% steel fiber, respectively. This behavior agrees with previous studies on concretes[43,85,88] and mortars[62]

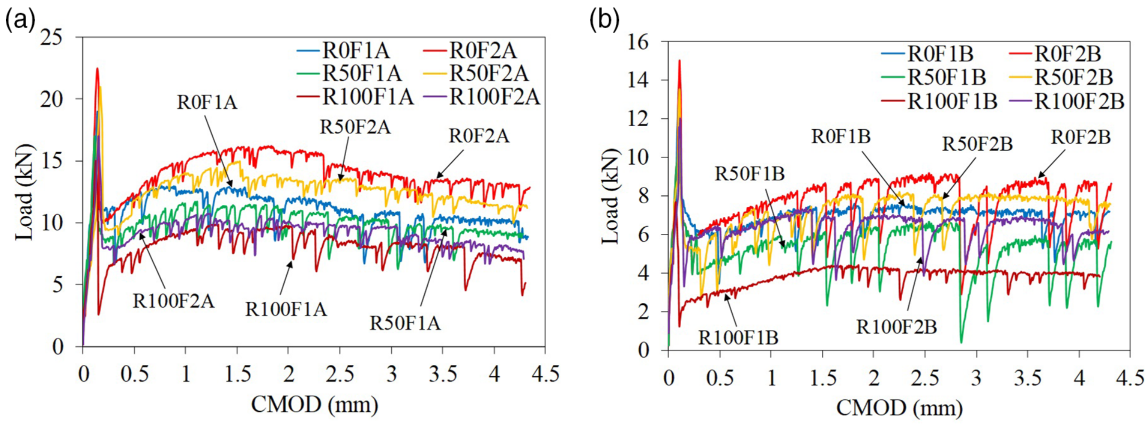

FIGURE 7 Load-CMOD relationships of different mixes at 28 days: (a) $w/c = 0.3$ and (b) $w/c = 0.5$. CMOD, crack mouth opening displacement

TABLE 6 Flexural test results of different mixes at 28 days

Mix	First crack load (kN)	Flexural tensile strength (MPa)	Residual flexural strength (MPa) at CMODs			
			0.5 mm	1.5 mm	2.5 mm	3.5 mm
R0F0A	–	4.12	–	–	–	–
R0F1A	13.3	6.89	3.62	3.88	3.65	3.20
R0F2A	13.9	7.79	3.80	5.14	4.71	4.25
R50F0A	–	3.76	–	–	–	–
R50F1A	12.4	6.30	3.10	3.35	3.32	3.07
R50F2A	13.0	7.14	3.78	4.38	4.18	3.66
R100F0A	–	3.17	–	–	–	–
R100F1A	10.2	5.33	2.23	3.04	2.82	2.60
R100F2A	10.7	6.20	3.00	3.15	3.22	2.64
R0F0B	–	2.96	–	–	–	–
R0F1B	9.1	4.37	1.95	2.30	2.15	2.00
R0F2B	9.5	4.91	2.27	2.84	2.84	2.67
R50F0B	–	2.79	–	–	–	–
R50F1B	8.2	4.05	1.42	1.86	1.75	1.60
R50F2B	8.5	4.50	2.10	2.40	2.35	2.30
R100F0B	–	2.36	–	–	–	–
R100F1B	7.7	3.69	0.99	1.37	1.32	1.25
R100F2B	8.0	4.16	1.90	2.20	2.05	1.98

Abbreviation: CMOD, crack mouth opening displacement.

and is due to the decrease in the stress between fiber and paste matrix with increasing V_f, leading to the delay in the creation and propagation of cracks in the concrete.[89] The less significant flexural strength enhancement from 1% to 2% V_f compared to that from 0% to 1% V_f agrees with the previous study on natural aggregate concrete.[90] As shown in Table 6, replacing natural coarse aggregates with RCAs caused a decrease in the flexural tensile and residual flexural strengths. At *w/c* of 0.3 and 0.5, mixes containing 50% RCA developed an approximately 9% and 7% lower flexural tensile strength and 1%–15% and 7%–27% lower residual flexural strength in comparison with companion mixes without RCA, respectively. Increasing *RA* from 50% to 100% led to a decreased flexural tensile and residual flexural strength. Mixes with 0.3 and 0.5 *w/c* containing 100% RCA developed an approximately 15% and 11% lower flexural tensile strength and 9%–28% and 8%–30% lower residual flexural strength in comparison with companion mixes containing 50% RCA, respectively. The lower flexural tensile and residual flexural strengths of concretes containing RCAs compared to those without RCA agree with previous studies on concrete with longitudinal reinforcement,[81] steel fiber-reinforced concrete[39,91] and unreinforced concrete,[55] and is because of the existence of weak ITZ in mixes containing RCAs.[81] As can be observed in Table 6, all the steel fiber-reinforced concrete mixes containing RCA developed a higher flexural tensile strength compared to the unreinforced mixes without RCA, indicating that incorporating steel fiber mitigated the adverse effect of replacing natural coarse aggregates with RCAs on the flexural capacity of the concrete.

Table 7 illustrates the comparison between the flexural strengths obtained from experimental results of this study and predictions obtained from existing models. As can be seen in the table, the model by Oluokun[75] exhibited the most accurate predictions of the flexural strength of specimens with *w/c* of 0.3, which was followed by ACI 318-11,[73] Ramadoss and Nagamani,[76] and Bhanja and Sengupta[92] models, respectively. It can also be seen that the model by Bhanja and Sengupta[92] developed the most accurate predictions of the flexural strength of specimens with *w/c* of 0.5, which was followed by Ramadoss and Nagamani,[76] Oluokun,[75] and ACI 318-11[73] models, respectively.

Flexural toughness index is one of the parameters for evaluating the ductility and energy absorption capacity of fiber-reinforced concretes.[43,88] Figure 8(a),(b) illustrate the variation of 28-day flexural toughness index of different steel fiber-reinforced mixes with CMODs for 0.3 and 0.5 *w/c*, respectively. Based on EN 14651,[49] toughness index was determined as total energy absorption rate at a specific CMOD (0.5, 1.5, 2.5, and 3.5 mm) to the energy absorption at the limit of proportionality, which is defined as a point where flexural cracking is started. As shown in Figure 8(a),(b), for a given V_f and *RA*, mixes with *w/c* of 0.3 had a higher toughness compared to those with *w/c* of 0.5. This is consistent with previous studies on conventional[68,93] and self-compacting concrete[94] and is owing to the higher residual flexural strength of mixes having 0.3 *w/c* compared to those with 0.5 *w/c*.[93] It can also be observed in the figures that, for a given *w/c* and *RA*, increasing V_f caused an increased toughness of the concrete, and the toughness increases became more pronounced at larger CMODs. This agrees with previous studies on conventional concrete[43,68,88,95] and is because an increased V_f results in an increased resistance of the concrete to restraint crack generation and propagation, leading to an increased ductility and energy absorption of concrete.[43] Incorporating RCAs led to a decreased toughness, and an increased *RA* caused a decreased toughness of concrete for a given *w/c* and V_f. This observation is because of the decreased residual flexural strength of concretes when natural coarse aggregates were replaced with RCAs.[96]

4.5 | Surface hardness

Figure 9(a),(b) show surface hardness of concrete mixes with 0.3 and 0.5 *w/c*, respectively. As shown in the figures, at a given curing age, mixes with 0.3 *w/c* had a higher surface hardness than those with 0.5 *w/c* for a given V_f and *RA*. This observation agrees with previous studies on unreinforced concrete[97,98] and is attributed to the higher strength of mixes with 0.3 *w/c* compared to those with 0.5 *w/c*.[98] As can also be seen in the figures, incorporating 1% steel fibers led to a 11%–18% and 2%–18% increase in the surface hardness of the concrete at 7 and 28 days, respectively. It is also observed that increasing V_f from 1% to 2% resulted in a 4%–15% and 2%–6% increase in the surface hardness of concrete at 7 and 28 days, respectively. The higher surface hardness of concretes with steel fibers than that of unreinforced concrete agrees with previous studies on self-compacting fly ash concrete[99,100] and light-weight concrete[101] and is because the high elastic modulus of steel fibers caused an increased resistance of the matrix against penetration.[102]

As shown in Figure 9(a),(b), for given *w/c*, V_f, and age of curing, incorporating RCAs caused a decreased surface hardness. This behavior agrees with previous studies on unreinforced concrete[55,103–105] and is owing to the more porous microstructure of concretes with RCAs in comparison with those with natural coarse aggregates, resulting in a less hard concrete surface in recycled aggregate concretes.[103,104] Concrete mixes containing 50%

TABLE 7 Comparison between experimental results of flexural strength and predictions by existing models for fiber-reinforced concrete

	Experimental results		ACI 318–11[73]		Oluokun[75]		Ramadoss and Nagamani[76]		Bhanja and Sengupta[92]	
Mix	f'_c (MPa)	f_r (MPa)	f_r (MPa) = $0.62(f'_c)^{0.5}$	Error (%)	f_r (MPa) = $0.79(f'_c)^{0.5}$	Error (%)	f_r (MPa) = $0.45(f'_c)^{0.67}$	Error (%)	f_r (MPa) = $0.275(f'_c)^{0.81}$	Error (%)
R0F0A	59.1	4.12	4.77	−15.7	6.07	−47.4	6.92	−68.0	7.49	−81.7
R0F1A	67.5	6.89	5.09	26.1	6.49	5.80	7.56	−9.81	8.34	−21.0
R0F2A	70.9	7.79	5.22	33.0	6.65	14.6	7.81	−0.37	8.68	−11.4
R50F0A	52.3	3.76	4.48	−19.2	5.71	−52.0	6.37	−69.6	6.78	−80.4
R50F1A	63.1	6.30	4.93	21.8	6.28	0.39	7.23	−14.8	7.90	−25.3
R50F2A	66.9	7.14	5.07	29.0	6.46	9.50	7.52	−5.33	8.28	−15.9
R100F0A	40.5	3.17	3.95	−24.5	5.03	−58.6	5.37	−69.5	5.51	−73.9
R100F1A	52.9	5.33	4.51	15.4	5.75	−7.80	6.42	−20.6	6.84	−28.4
R100F2A	56.9	6.20	4.67	24.6	5.95	3.97	6.73	−8.70	7.25	−16.9
AAE (%)				**23.3**		**22.2**		**29.6**		**39.4**
R0F0B	27.6	2.96	3.26	−10.0	4.15	−40.2	4.15	−40.4	4.04	−36.5
R0F1B	30.8	4.37	3.44	21.3	4.38	−0.33	4.47	−2.34	4.42	−1.06
R0F2B	32.4	4.91	3.53	28.1	4.50	8.42	4.62	5.77	4.60	6.29
R50F0B	24.1	2.79	3.04	−9.09	3.88	−39.0	3.79	−36.0	3.62	−29.8
R50F1B	27.2	4.05	3.23	20.2	4.12	−1.73	4.11	−1.61	3.99	1.40
R50F2B	28.8	4.50	3.33	26.1	4.24	5.79	4.27	4.98	4.18	7.05
R100F0B	15.3	2.36	2.43	−2.76	3.09	−30.9	2.79	−18.6	2.51	−6.17
R100F1B	17.6	3.69	2.60	29.5	3.31	10.2	3.07	16.7	2.81	23.9
R100F2B	19.9	4.16	2.77	33.5	3.52	15.3	3.34	19.8	3.10	25.5
AAE (%)				**20.1**		**16.9**		**16.2**		**15.3**

Note: f'_c, 28-day compressive strength; f_r, 28-day flexural strength.
Abbreviation: AAE, average absolute error.

RCA experienced a 4%–13% and 5%–12% lower surface hardness at 7 and 28 days compared to those without RCA, respectively. It is also shown in the figures that the surface hardness of concrete decreased with an increase in *RA* from 50% to 100%. Mixes containing 100% RCA experienced a 14%–24% and 8%–22% lower surface hardness at 7 and 28 days compared to those containing 50% RCA, respectively.

As can be observed in Figure 9(a),(b), steel fiber-reinforced concrete mixes containing 50% RCA developed a nearly similar 28-day and a higher 7-day surface hardness compared to the unreinforced mixes without RCA.

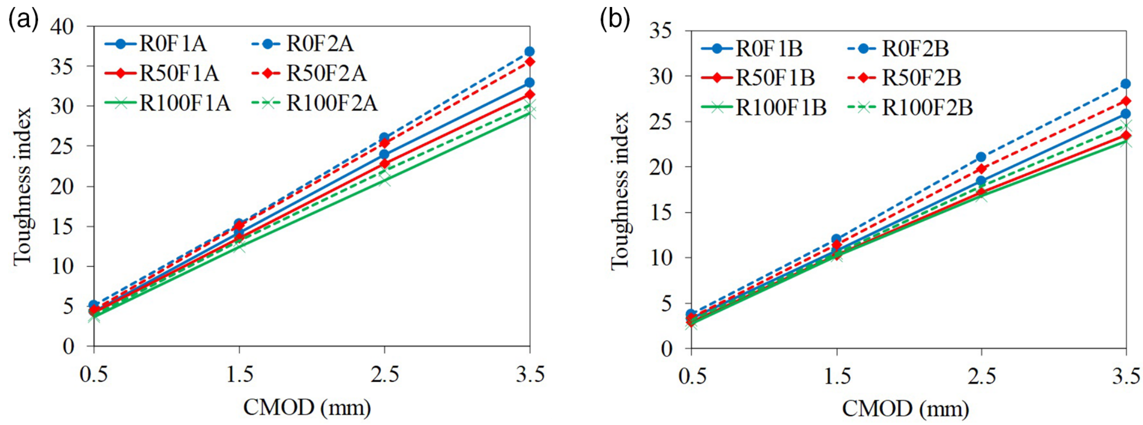

FIGURE 8 Variation of toughness index of different mixes with CMOD at 28 days: (a) $w/c = 0.3$ and (b) $w/c = 0.5$. CMOD, crack mouth opening displacement

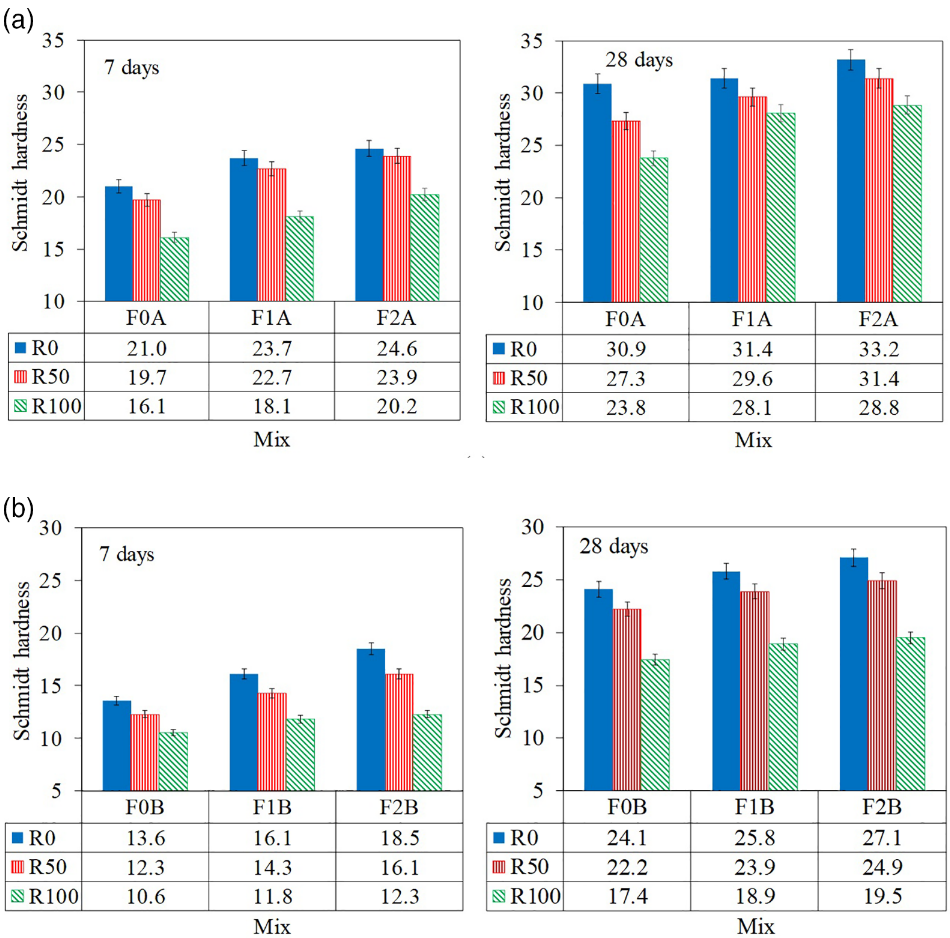

FIGURE 9 Schmidt surface hardness of different mixes at 7 and 28 days: (a) $w/c = 0.3$ and (b) $w/c = 0.5$

Steel fiber-reinforced concrete mixes containing 100% RCA developed a lower surface hardness compared to the unreinforced mixes without RCA, and the hardness decreases were less significant in HSC mixes compared to those in NSC mixes.

4.6 | Surface abrasion

Surface abrasion resistance, as an important parameter to investigate the performance of dam, pavement and spillway concrete, mainly depends on the concrete compressive strength and surface hardness.[106] Figure 10(a),(b) show the surface abrasion test results of mixes with *w/c* of 0.3 and 0.5, respectively. At a given curing age, mixes with *w/c* of 0.3 had a lower abrasion mass loss compared to those with *w/c* of 0.5 for a given V_f and *RA*. This observation agrees with previous studies on unreinforced concrete[107–109] and is because of the lower porosity and higher strength of mixes having less *w/c*.[108] It can also be observed in the figures that, incorporating steel fibers caused a decrease in the mass loss of the concrete, and the decreases were more significant in HSC mixes compared to those in NSC mixes. HSC mixes with 1% steel fibers experienced an approximately 18% and 24% lower abrasion mass loss and NSC mixes with 1% steel fiber experienced an approximately 14% and 12% lower abrasion mass loss compared to companion unreinforced mixes at 7 and 28 days, respectively. This observation is because steel fiber has a high hardness and incorporating steel fiber in the concrete causes a denser and stronger surface, leading to the improved ability to abrasion compared to concrete without steel fiber.[102] As also observed from the figures, an increase in V_f from 1% to 2% led to an approximately 10% and 16% decrease in the abrasion mass loss of HSC mixes and approximately 8% and 6% decrease in the abrasion mass loss of NSC mixes at 7 and 28 days, respectively. This behavior agrees with previous studies on conventional concrete[68,102,110] and geopolymer mortar.[111]

It is shown in Figure 10(a),(b) that, incorporating RCAs caused an increase in the abrasion mass loss of the concrete for a given *w/c*, V_f and curing age. This behavior agrees with previous studies on unreinforced concrete[108,112–114] and is owing to the lower quality of RCAs compared to that of natural coarse aggregates, which led to the lower strength and resistance of concretes containing RCAs to abrasion.[114] F0, F1, and F2 mixes containing 50% RCA developed an approximately 8%, 11%, and 13% higher mass loss at 7 days and an approximately 12%, 8%, and 17% higher mass loss at 28 days compared to those companion mixes without RCA, respectively. As also observed from the figures, the surface abrasion mass loss of the concrete mixes increased with increasing *RA*, which is consistent with previous studies on unreinforced concrete.[107,108] HSC mixes containing 100% RCA exhibited an approximately 15% and 28% higher mass loss and NSC mixes containing 100% RCA exhibited an approximately 18% and 17% higher mass loss at 7 and 28 days compared to those companion mixes containing 50% RCA, respectively.

As shown in Figure 10(a),(b), steel fiber-reinforced concrete mixes containing 50% RCA developed a lower abrasion mass loss in comparison with the unreinforced mixes without RCA. In HSC series, steel fiber-reinforced mixes containing 100% RCA developed a nearly similar mass loss, whereas in NSC series, steel fiber-reinforced mixes containing 100% RCA developed a slightly higher mass loss compared to the companion unreinforced mixes without RCA. These observations indicate that normal and high strength steel fiber-reinforced mixes containing 50% RCA and high strength steel fiber-reinforced mixes containing 100% RCA had a higher or similar abrasion resistance compared to the unreinforced conventional concrete.

4.7 | Water absorption

Results of water absorption tests on different mixes with 0.3 and 0.5 *w/c* at 28 days are shown in Figure 11(a),(b). As shown in the figures, for a given V_f, R0, R50, and R100 mixes with *w/c* of 0.3 had an approximately 19%, 23%, and 32% lower water absorption than those companion mixes with *w/c* of 0.5, respectively. This observation is owing to an increased porosity of the mix with an increase in *w/c*.[115,116] It is also observed that adding steel fibers led to a decreased water absorption. Mixes with 1% steel fiber had approximately 10% lower absorption compared to those without steel fiber. As also shown in the figures, increasing V_f led to the reduction of the water absorption of the mixes. At *w/c* of 0.3, R0, R50, and R100 mixes containing 2% steel fiber developed 5%, 10%, and 9% lower water absorption and at *w/c* of 0.5, they developed 5%, 8%, and 3% lower water absorption compared to companion mixes containing 1% steel fiber, respectively. The lower water absorption of the mixes containing steel fiber than those without steel fiber agrees with previous studies on conventional concrete[37,112,117,118] and is because steel fibers decrease the permeable voids of the mix by restricting the formation and propagation of cracks, leading to a denser-microstructure concrete.[119,120]

As shown in Figure 11(a),(b), for a given *w/c* and V_f, 50% replacement of natural coarse aggregates with RCAs caused an increase in the water absorption, and the absorption increases became more pronounced in NSC mixes than those in HSC mixes. At *w/c* of 0.3 and 0.5, mixes containing 50% RCA developed an approximately 10% and 17% higher water absorption compared to companion mixes without RCA, respectively. It is also observed from the figures that the absorption of mixes increased with an increased *RA*. At *w/c* of 0.3 and 0.5, mixes containing 100% RCA exhibited an approximately 18% and 33% higher water absorption in comparison with companion mixes containing 50% RCA, respectively. The higher absorption of mixes containing RCAs than those without RCA agrees with previous studies on unreinforced concrete[21,57,109] and is because of the more absorption of RCAs compared to that of natural coarse aggregates, as was presented in Table 2. As can be observed in Figure 11(a), in HSC series, mixes with 1% steel fiber and 50% RCA developed a nearly similar water absorption and mixes with 2% steel fiber and 50% RCA developed a lower water absorption in comparison with the companion control mix without steel fiber and RCA. It is shown in Figure 11(b) that, in NSC series, mixes with 1% steel fiber and 50% RCA developed a higher water absorption, but mixes with 2% steel fiber and 50% RCA developed a similar water absorption in comparison with the companion control mix without steel fiber and RCA. All steel fiber-reinforced concrete mixes with 100% RCA

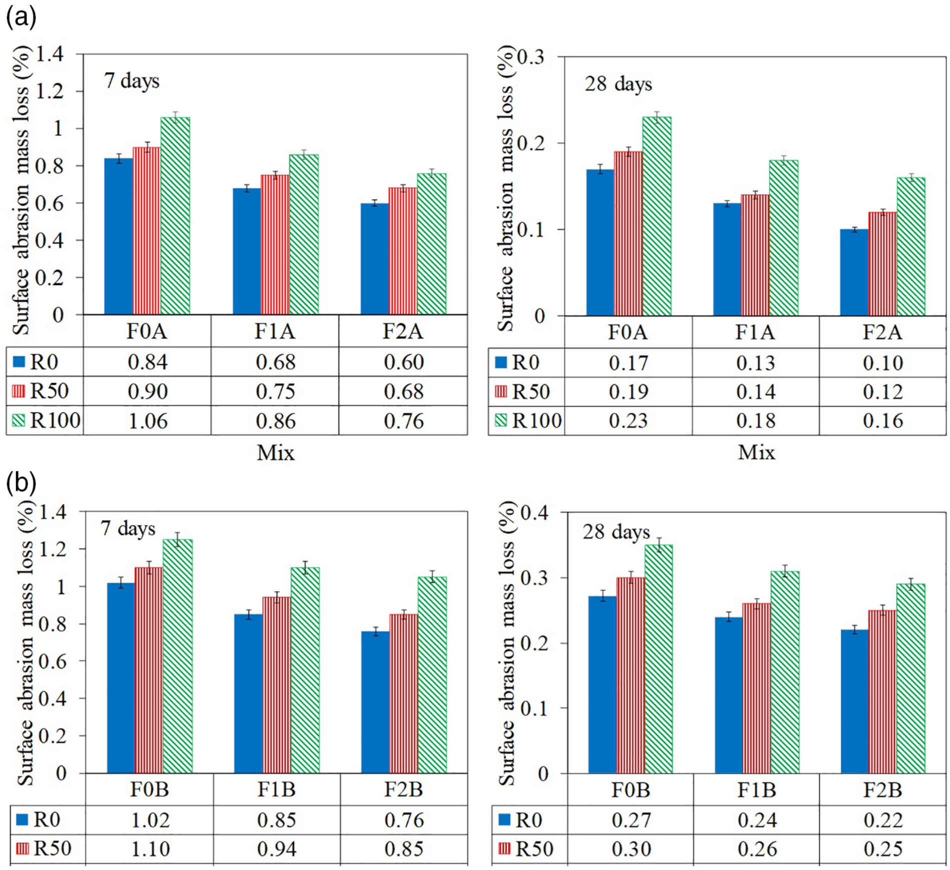

FIGURE 10 Surface abrasion mass loss of different mixes at 7 and 28 days: (a) $w/c = 0.3$ and (b) $w/c = 0.5$

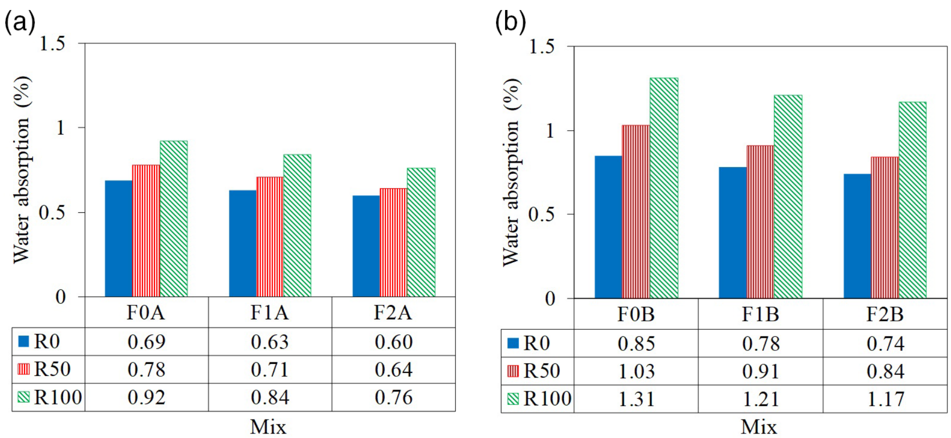

FIGURE 11 Water absorptionof different mixes at 28 days: (a) $w/c = 0.3$ and (b) $w/c = 0.5$

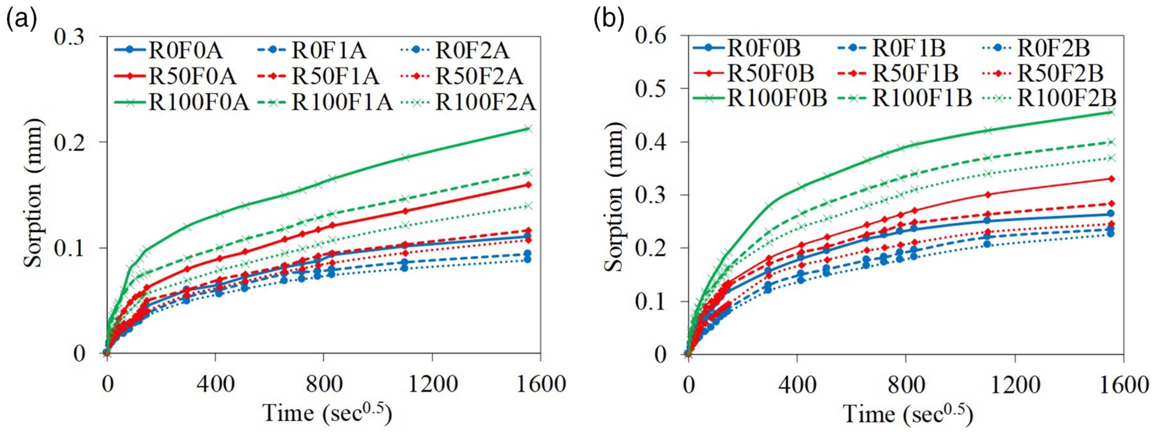

FIGURE 12 Sorptivity test results of different mixes: (a) $w/c = 0.3$ and (b) $w/c = 0.5$

developed a higher absorption in comparison with companion control mixes.

4.8 | Sorption

Sorptivity is the concrete ability in absorbing and transporting water by capillary suction through the microstructure of the concrete.[121] Figure 12(a),(b) illustrate the sorptivity test results of different mixes with 0.3 and 0.5 *w/c*, respectively. As shown in the figures, sorption rate of concretes decreased with an increased time. This observation is because initially larger capillary pores are filled with water and then finer pores are filled with water by increasing time.[122] It is shown in the figures that, for a given V_f and *RA*, mixes with *w/c* of 0.3 had a lower water sorptivity in comparison with those with *w/c* of 0.5. This observation agrees with previous studies on unreinforced conventional concrete,[123,124] self-compacting concrete[21] and steel fiber-reinforced concrete,[69] and is due to the higher capillary porosity and larger pore structure of mixes with 0.5 *w/c* than those with 0.3 *w/c*.[124] At a given *w/c* and *RA*, incorporating steel fibers led to a decreased sorptivity of the concrete, and an increased V_f caused a decrease in the concrete sorptivity. The lower sorptivity of the mixes containing steel fiber compared to those without steel fiber agrees with previous studies on conventional concrete[69,112,125] and is because steel fibers discontinue the capillary pores and reduce the volume of permeable voids of concrete.[125]

It is shown in Figure 12(a),(b) that, for a given *w/c* and V_f, replacing natural coarse aggregates with RCAs caused an increased sorptivity of the concrete. It is also shown that water sorptivity of concrete increased with an increased *RA*. The higher water sorptivity of the mixes containing RCAs compared to those without RCA agrees with previous studies on unreinforced concrete[126,127] and steel fiber-reinforced concrete[12,112] and is because of the porous structure of the attached mortar to RCAs.[112] As shown in Figure 12(a),(b), steel fiber-reinforced concrete mixes containing 50% RCA developed a nearly similar or even lower sorptivity in comparison with the conventional concrete without steel fiber and RCA.

5 | CONCLUSIONS

Findings of the study on the mechanical and durability performance of steel fiber-reinforced concrete produced with RCA have been presented. Below are key conclusions of this study:

1. At a given V_f and *RA*, concretes with 0.3 *w/c* exhibit a higher unit weight, compressive, splitting tensile and flexural strength, flexural toughness, surface hardness, and abrasion resistance, and a lower water absorption and sorptivity compared to those with 0.5 *w/c*. Concrete produced with RCA exhibits a lower unit weight, compressive, splitting tensile and flexural strength, flexural toughness, surface hardness, and abrasion resistance, and a higher water absorption and sorptivity in comparison with conventional concrete.
2. Increases in compressive, splitting tensile and flexural strength, flexural toughness, surface hardness, and abrasion resistance, and decreases in absorption and sorptivity of concrete with an increased V_f from 1% to 2% are less significant compared to those from 0% to 1%. This may be because of the less uniform dispersion of steel fibers in concrete mix with V_f of 2% compared to that with V_f of 1%.
3. An increased flexural tensile strength and residual flexural strength of concrete incorporating steel fiber is more significant in concrete having 0.3 *w/c*

compared to that with 0.5 *w/c*. This is because the applied load after cracking in concretes is sustained by mechanical interlocking and friction between fibers and paste matrix, and HSC has a stronger paste matrix in comparison with NSC.
4. At *RA* of 50%, incorporating only 1% steel fiber develops a concrete mix with a similar or even better mechanical and durability performance compared to unreinforced natural aggregate concrete with 0.3 *w/c* and a similar mechanical and durability performance compared to unreinforced natural aggregate concrete with 0.5 *w/c*. At *RA* of 100%, incorporating 2% steel fiber develops a concrete mix with similar properties to unreinforced natural aggregate concrete with 0.3 *w/c*, but inferior properties to unreinforced natural aggregate concrete with 0.5 *w/c*.

The results of this study indicate that properly designing concrete mixes with steel fiber can compensate the inferior characteristics of recycled aggregate concrete even at *RA* of 100%. This promising finding helps in better understanding the development of sustainable waste-based concretes with properties similar or even better than conventional concrete.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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