Influence of double hooked-end steel fibers and slag on mechanical and durability properties of high performance recycled aggregate concrete

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This paper presents a study on the properties of sustainable high performance steel fiber-reinforced concretes that were manufactured with recycled concrete aggregates (RCA). Natural coarse aggregates were replaced by RCA derived from parent concretes with compressive strengths of 40 and 80 MPa at volume replacement ratios of 50% and 100%. High performance concretes (HPC) were manufactured using double hooked-end steel fibers added at a fiber volume fraction of 1%, and in some of the mixes 30% of ordinary Portland cement was replaced by slag. Along with their mechanical properties, the water absorption, electrical resistivity, and shrinkage of the concrete mixes were evaluated. The results indicate that HPC with desirable properties can be produced using RCA derived from a high-strength parent con-crete. The addition of steel fibers significantly increases the mechanical properties of recycled aggregate concretes. Replacing natural aggregates with RCA of lower strength adversely affects the durability properties of the concrete. However, concretes produced with a higher quality RCA and those containing slag and steel fibers exhibit reduced water absorption and shrinkage compared to plain natural aggregate concrete. The findings of this research are highly promising for the development of HPC with reduced environmental impact.

Keywords: Recycled aggregate concrete, High performance concrete, Double hooked-end steel fibers, GGBS, Mechanical properties, Durability properties

1. Introduction

The amount of construction and demolition waste (C&DW) has increased enormously over the last decade across the world [1]. A significant amount of this waste is from demolished concrete structures. It is reported that around 320–380 million tons of C&DW is being produced annually only in the European Union [2]. The replacement of natural aggregates (NA) with recycled concrete aggregates (RCA) not only reduces the need for the quarried aggregates, but it also often leads to a reduction in the transportation costs and emission [3]. Recycling and reusing the waste concrete is favorable and essential from the viewpoint of environmental preservation and resource efficiency [4–6]. Moreover, the development of recycled aggregate concrete with incorporating RCA as an alternative to conventional concrete is necessary due to the shortage of NA supply in some parts of the world [7]. Generally, lower properties of RCA compared to those of NA often results in concretes with reduces physical, mechanical, and durability properties [8,9]. However, it has been reported that the use of an appropriate mix design [10,11] and the incorporation of mineral admixtures [12] can lead to a concrete with comparable performance to those of natural aggregate concrete (NAC). Pepe et al. [13] have recently proposed a novel mix design methodology for recycled aggregate concrete that takes into account the attached mortar on RCA.

The use of mineral admixtures has increased significantly over the recent years as a result of an increase in the environmental awareness. Currently, Portland cement concrete production accounts for around 7% of carbon dioxide (CO_2) emissions annually and its reduction is a global issue [14]. The current approach to overcome this problem is to replace ordinary Portland cement (OPC) with mineral admixtures. Since many mineral admixtures are by-products of other industries, these waste by-products can be used to reduce the amount of cement required and consequently produce more environmentally-sustainable concrete [15,16]. Some of the more commonly available mineral admixtures include the silica fume, fly ash, and ground granulated blast-furnace slag (GGBS) [17,18]. It is well documented that GGBS is a beneficial additive for concrete and it can improve properties of concrete due to its pozzolanic effect [19,20]. The GGBS-blended concrete can reduce the porosity of concrete, change the

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Table 1
Chemical composition and physical properties of cementitious materials.

Item	Cementitious materials (%)	
	Cement	GGBS
SiO_2	21.2	37.2
Al_2O_3	5.4	11.4
Fe_2O_3	3.4	0.8
MgO	1.4	8.3
Na_2O	–	1.0
K_2O	–	–
CaO	63.9	41.2
Compounds		
C_3S	51.5	–
C_2S	22.0	–
C_3A	6.4	–
C_4AF	10.5	–
Physical properties		
Specific gravity (kg/m^3)	3.150	2.720
Specific surface (m^2/kg)	300	474

Table 2
Aggregate grading.

Sieve Size	Passing Percentage (%)			
	Fine aggregate	Coarse aggregate	R40	R80
3/4 in. (19 mm)	100.0	97.6	95.2	97.0
1/2 in. (12.5 mm)	100.0	62.4	53.4	57.2
3/8 in. (9.5 mm)	100.0	32.3	30.0	28.1
1/4 in. (6.35 mm)	100.0	6.3	8.3	7.4
No. 4 (4.75 mm)	97.0	0.4	2.0	2.4
No. 8 (2.36 mm)	78.3	0.1	0.2	0.5
No. 16 (1.18 mm)	50.9	–	–	–
No. 30 (0.6 mm)	24.8	–	–	–
No. 50 (0.3 mm)	4.6	–	–	–
No. 100 (0.15 mm)	1.1	–	–	–
No. 200 (0.075 mm)	0.6	–	–	–

Note: R40 and R80 are recycled aggregate obtained from parent concrete with the 28 day compressive strength of 40 and 80 MPa, respectively.

mineralogy of the cement hydrates, and consequently improve the durability properties of concrete [21,22].

The global demand for high performance concrete (HPC) has significantly increased over the recent years [23,24]. HPC can be designed to have a higher workability and mechanical properties as well as improved durability compared to those of the traditional concrete [25,26]. However, only a few studies [27–29] have been reported to date on the use of RCA in HPC. It is now understood that the quality of parent concrete from which RCA are derived has an important effect on the properties of the new concrete [30]. It has been shown [8] that HPC can be successfully produced by the use of coarse RCA that were derived from parent concrete with compressive strengths higher than 60 MPa. Despite its large number of benefits, the higher strength of HPC causes its high sensitivity to early age cracking that can seriously degrade the service life of structures [31]. Using fibers in concrete is recognized as a promising way to overcome this weakness and produce a material with a higher tensile strength [32,33], flexural strength [34,35], ductility [36,37], and energy absorption capacity that results from controlled crack propagation [38].

The objective of the current study was to investigate the effect of RCA that were derived from parent concretes with compressive strengths of 40 and 80 MPa on the properties of HPC. The replacement of the natural coarse aggregates with RCA at replacement ratios of 50% and 100% were considered. Moreover, the influence of the replacement of the cement with 30% GGBS has been investigated. Finally, double hooked-end (DHE) steel fibers were added to some of the mixes at a volume fraction of 1%. To the best knowledge of the authors, this is the first study to investigate the effect of DHE steel fibers in HPC containing RCA and the first to investigate the properties of fiber-reinforced recycled aggregate concrete containing GGBS. Furthermore, a very limited number of studies have been conducted on the durability properties, such as water absorption, electrical resistivity, and shrinkage of recycled aggregate concretes made with GGBS [39–41]. The compressive strength, splitting tensile strength, flexural strength, water absorption, electrical resistivity, and shrinkage of concretes were evaluated. The findings of this research have the potential to significantly contribute toward expanding the use of HPC manufactured with RCA and steel fibers to different structural applications.

2. Experimental program

2.1. Characteristics of materials

2.1.1. Cement and GGBS

ASTM Type 1 Portland cement and GGBS with specific surface of 300 and 474 m^2/kg, respectively, were used in concrete mixes. The chemical composition and physical properties of these materials are given in Table 1.

2.1.2. Aggregates

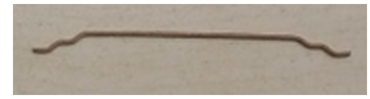
Crushed gravel with a nominal maximum size of 19 mm and sand with a 3.4 fineness modulus were used as NA. Coarse aggregates and sand were employed at an equal volume fraction of 50%. Two types of RCA were derived from parent concretes having compressive strengths of 40 and 80 MPa. The RCA were obtained from concretes that were prepared in the laboratory using the same NA as the control mixes, which were crushed at the age of 28 days. To obtain similar grading curves and maximum aggregate sizes to those of natural coarse aggregate, the RCA were sieved after crushing. The size distribution of NA and RCA are listed in Table 2, and their physical properties are given in Table 3. As expected, natural coarse aggregate had a higher density and lower water absorption compared to those of RCA. Moreover, the physical properties of RCA improved with an increase in the strength of the parent concrete. Pepe et al. [42] reported that the processing procedure has a significant influence on the physical properties of RCA [42]. It was shown that autogenous cleaning led to enhancement of properties of RCA, particularly by reducing the attached mortar content on RCA surface, and subsequently reducing their water absorption capacity. In the current study the attached mortar

Table 3
Physical properties of natural and recycled concrete aggregates.

Aggregate type	Maximum size aggregate (mm)	Water absorption (%)	Specific gravity (kg/m^3)	Attached mortar (%)	Moisture content (%)
Fine aggregate	4.75	1.35	2.62	–	1.07
Coarse aggregate	19.0	0.73	2.66	–	0.52
R40	19.0	4.90	2.41	38	2.28
R80	19.0	4.12	2.47	24	1.84

Note: R40 and R80 are recycled aggregate obtained from parent concrete with the 28 day compressive strength of 40 and 80 MPa, respectively.

Table 4
Properties of steel fiber.

Type and shape of fiber	Length *l* (mm)	Diameter *d* (mm)	Aspect ratio *l/d*	Density (g/cm^3)	Tensile strength (N/mm^2)	Picture
Double hooked-end steel fiber (DHE)	60	0.9	65	7.8	2300	

content of RCA was evaluated using the hydrochloric acid dissolution method [43], and the results are presented in Table 3. It was observed that the attached mortar content reduced with increasing parent concrete strength.

2.1.3. Superplasticizer

To achieve the desired workability in different concrete mixtures, a Carboxylic 110M, supplied by BASF, was used as a superplasticizer in all mixes.

2.1.4. Steel fiber

DHE steel fibers with a length of 60 mm and an aspect ratio of 65 were used in this study. The properties and physical appearance of fibers are given in Table 4.

2.2. Concrete mixes

All concrete mixes had a total binder content of 500 kg/m^3 and they were produced with an effective water-binder ratio of 0.3. The absolute volume method [44] was used to design the concrete mixes with mixture proportions shown in Table 5. Four series of concrete mixes were produced with each series containing five different mixes. HPC in Series A were manufactured with different RCA and without GGBS or steel fibers. In series B and D, Portland cement was replaced by 30% GGBS and HPC in Series C and D included 1% DHE steel fibers. RCA were added to the mixes at a volume replacement of natural coarse aggregates of 50% and 100%. The RCA derived from a parent concrete with a compressive strength of 40 and 80 MPa, are referred to R40 and R80, respectively. NA and sand were used in saturated surface dry (SSD) condition, while RCA were added at 80% saturation. Table 5 shows the effective water used in the mixes; in the case of recycled aggregate concretes additional water was used during mixing to keep the effective water-binder ratio constant among mixes. In Table 5, the content of the superplasticizer is given as a percentage of the total mass of the binder. To determine the workability of fresh concrete, slump tests were performed as per ASTM C143 [45] during the preparation of the concrete mixes. Fig. 1 shows the appearance of fresh concrete during the slump test for both the plain concrete and concrete reinforced with 1% DHE steel fibers.

2.3. Specimens molding and curing

The details of the specimen casting and testing methods employed in this study are given in Table 6. As can be seen in the table, 100 mm cubes were used to determine the compressive strength, water absorption by immersion, and electrical resistivity, whereas 100 × 200 mm cylinders were used to determine the splitting tensile strength of the concrete. The prismatic beams with dimensions of 150 × 150 × 600 mm and 75 × 75 × 285 mm were used to measure the flexural strength and shrinkage of the concrete, respectively. The specimens were cast in steel molds and compacted on a vibration table. They were demolded after approximately 24 h and were then exposed to lime-saturated water at 23 °C and 100% relative humidity until their testing ages. The compressive strength and electrical resistivity tests were performed at 7, 28 and 91 days, whereas the remaining tests were conducted after 28 days of curing.

Table 5
Mix proportions of concrete mixes.

Mix No.	Series	Mixture ID	Effective *w/b*	Effective water	Cement	GGBS	Aggregate				Steel fiber	SP (%)	Slump (mm)
							Natural		Recycled				
							NFA	NCA	R80	R40			
1	A	NAC	0.3	150	500	–	881	894	–	–	–	1.1	210
2		R80-50	0.3	150	500	–	881	447	415	–	–	1.1	200
3		R80-100	0.3	150	500	–	881	–	830	–	–	1.1	210
4		R40-50	0.3	150	500	–	881	447	–	405	–	1.1	215
5		R40-100	0.3	150	500	–	881	–	–	810	–	1.1	225
6	B	NAC-GGBS30	0.3	150	350	150	870	883	–	–	–	1.1	190
7		R80-50-GGBS30	0.3	150	350	150	870	441	410	–	–	1.1	205
8		R80-100-GGBS30	0.3	150	350	150	870	–	820	–	–	1.1	200
9		R40-50-GGBS30	0.3	150	350	150	870	441	–	400	–	1.1	200
10		R40-100-GGBS30	0.3	150	350	150	870	–	–	800	–	1.1	210
11	C	NAC-S1	0.3	150	500	–	868	881	–	–	78	1.4	135
12		R80-50-S1	0.3	150	500	–	868	440	409	–	78	1.4	130
13		R80-100-S1	0.3	150	500	–	868	–	818	–	78	1.4	125
14		R40-50-S1	0.3	150	500	–	868	440	–	399	78	1.4	140
15		R40-100-S1	0.3	150	500	–	868	–	–	798	78	1.4	135
16	D	NAC-GGBS30-S1	0.3	150	350	150	857	870	–	–	78	1.4	130
17		R80-50-GGBS30-S1	0.3	150	350	150	857	435	404	–	78	1.4	120
18		R80-100-GGBS30-S1	0.3	150	350	150	857	–	808	–	78	1.4	135
19		R40-50-GGBS30-S1	0.3	150	350	150	857	435	–	394	78	1.4	130
20		R40-100-GGBS30-S1	0.3	150	350	150	857	–	–	788	78	1.4	115

Note: The abbreviations NFA, NCA, R80, and R40 refer to natural fine aggregate, natural coarse aggregate, 80 MPa recycled concrete aggregate, and 40 MPa recycled concrete aggregate, respectively.

(a) (b)

Fig. 1. Appearance of fresh concrete in slump test: (a) plain concrete and (b) concrete reinforced with 1% DHE steel fiber.

Table 6
Details of the specimens and test methods utilized to determine properties of recycled aggregate concretes.

Property	Test standard	Specimen size	Curing age
Compressive strength	ASTM C39	100 mm cube	7, 28, and 91 days
Splitting tensile strength	ASTM C496	100 × 200 mm cylinder	28 days
Flexural strength	BS EN 14651	150 × 150×600 mm prism	28 days
Water absorption	ASTM C642	100 mm cube	28 days
Electrical resistivity	–	100 mm cube	7, 28, and 91 days
Shrinkage	ASTM C157	75 × 75×285 mm prism	28 days

2.4. Testing methods

2.4.1. Compressive, splitting tensile and flexural strengths

Compressive and splitting tensile strength tests were performed using a 3000-KN universal compression machine in accordance with ASTM C39 [46] and ASTM C496 [47], respectively. The flexural strength tests were carried out as per BS EN 14651 [48].

2.4.2. Water absorption

The water absorption tests were performed on cubic specimens in accordance with ASTM C642 [49]. The water absorption of specimens was calculated using the difference between the weights of oven dried samples and specimens that were immersed in the water tank for 7 days.

2.4.3. Specific electrical resistivity

The specific electrical resistivity was measured with the AC-Impedance spectroscopy, with a 1.0 kHz frequency and a 1.0 MΩ final capacity. All the specimens were tested at saturated surface dry conditions and a layer of cement mortar was applied between the surface of concrete and copper plates to measure the electrical resistivity accurately.

2.4.4. Shrinkage

The free shrinkage test was performed on prismatic specimens in accordance with ASTM C157 [50]. The shrinkage samples were moist cured inside the molds for 24 h covered with plastic sheets to protect them from dripping water, and they were demolded thereafter. Upon removal of specimens from the molds, the samples were maintained in lime-saturated water for 30 min to minimize variation in length due to variation in temperature. Then the specimens were removed from water storage, wiped with a damp cloth and the initial comparator reading was measured immediately. As per ASTM C157, the shrinkage specimens were wet cured in lime-saturated water at 23 °C until they reached the age of 28 days. It is known that beyond 28 days the autogenous shrinkage is very limited and further shrinkage is mostly attributed to self-desiccation [51,52]. The shrinkage measurements were taken on the air-stored specimens at a room with a relative humidity of 50% and temperature of 23 °C, and consecutive reading were carried out after curing of 4 days and 1, 2, 4, 8, 16, 32, and 64 weeks.

3. Results and discussions

3.1. Compressive strength

The compressive strength results of different mixes are shown in Figs. 2 and 3. It can be seen that the compressive strength of mixes prepared with 80 MPa RCA is equal to or slightly higher than that of the NAC mix at all test ages. The replacement of NA with 40 MPa RCA resulted in a reduction in the compressive strength of concrete. The results also indicate that the compressive strength of mixes manufactured with 100% RCA is slightly lower than that of the corresponding mixes with 50% RCA. There are several factors including the amount of attached mortar, physical properties of RCA, and strength of the parent concrete that affect the strength of recycled aggregate concretes. The improvement in the strength of the 80 MPa RCA mixes with 50% replacement ratio can be explained by the further hydration products that resulted from the mortar attached on RCA. On the other hand, the reduction seen in the strength of the concrete with 100% RCA can be attributed to the weakness of RCA compared to NA, the influence of which becomes more significant in these mixes due to the increased content. The results further indicate that the compressive strength of R80-50 and R80-100 mixes were 3% and 1% higher than that of NAC mix, respectively, whereas the strength of R40-50 and R40-100 mixes were 5% and 9% lower than that of NAC mix, respectively. Similarly, the higher strength of the 80 MPa RCA mixes can be explained by the higher strength of their parent concrete com-

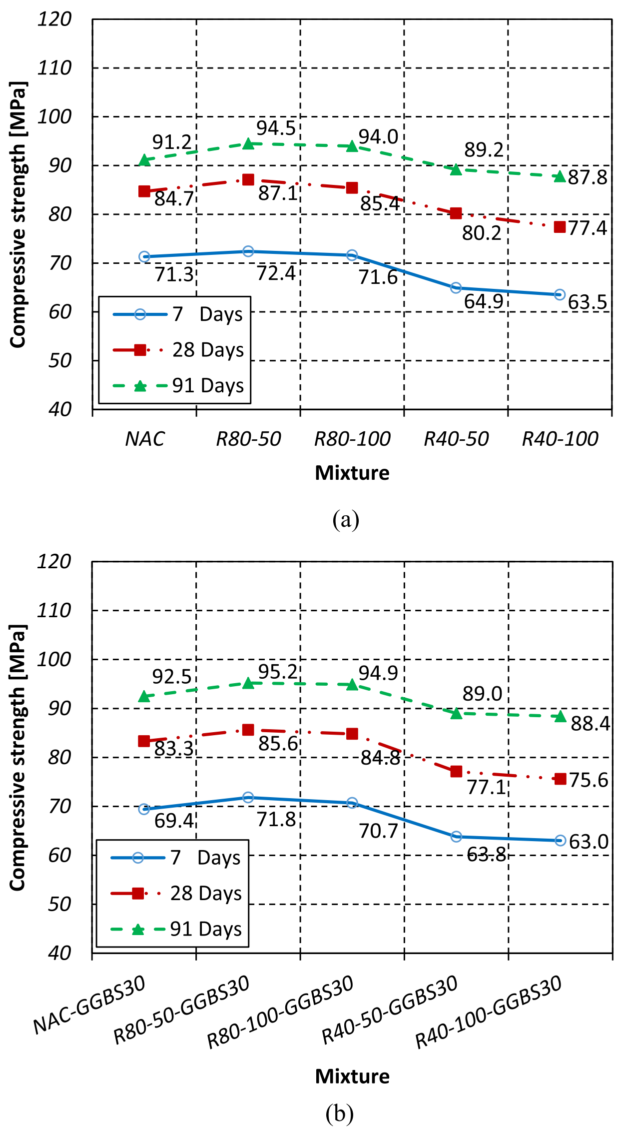


Fig. 2. Compressive strength of recycled aggregate concretes containing: (a) 0% GGBS and (b) 30% GGBS.

pared to that of the 40 MPa RCA. The quality of the two interface zones between the new and aged mortar, and the aged mortar with the raw aggregate is an important factor that significantly affects the properties of recycled aggregate concrete [53]. It is expected that the old ITZ between the aged mortar and the raw aggregate of RCA, particularly in case of RCA derived from concrete with a lower strength to be weaker than the new ITZ between the new mortar and RCA. Hence, the old ITZ could be the first surface that the crack develops. Consequently, R40-100 mix owing to the higher amount of attached mortar with low quality exhibited the lowest compressive strength.

As can be seen in Fig. 2, the substitution of OPC with 30% GGBS by weight led to a slight reduction in the compressive strength of concrete mixes at 7 and 28 days. However, the compressive strength of the mixes containing GGBS was equal to or slightly higher than those of the NAC mix at the testing age of 91 days. Introducing GGBS can result in an increase in the cohesiveness of the cementitious matrix, which reduces the induction of micro-cracks leading to an increased strength of concrete [54]. Moreover, GGBS fills the capillary pores of cement matrix and consequently improves the properties of the interfacial transition zone (ITZ)

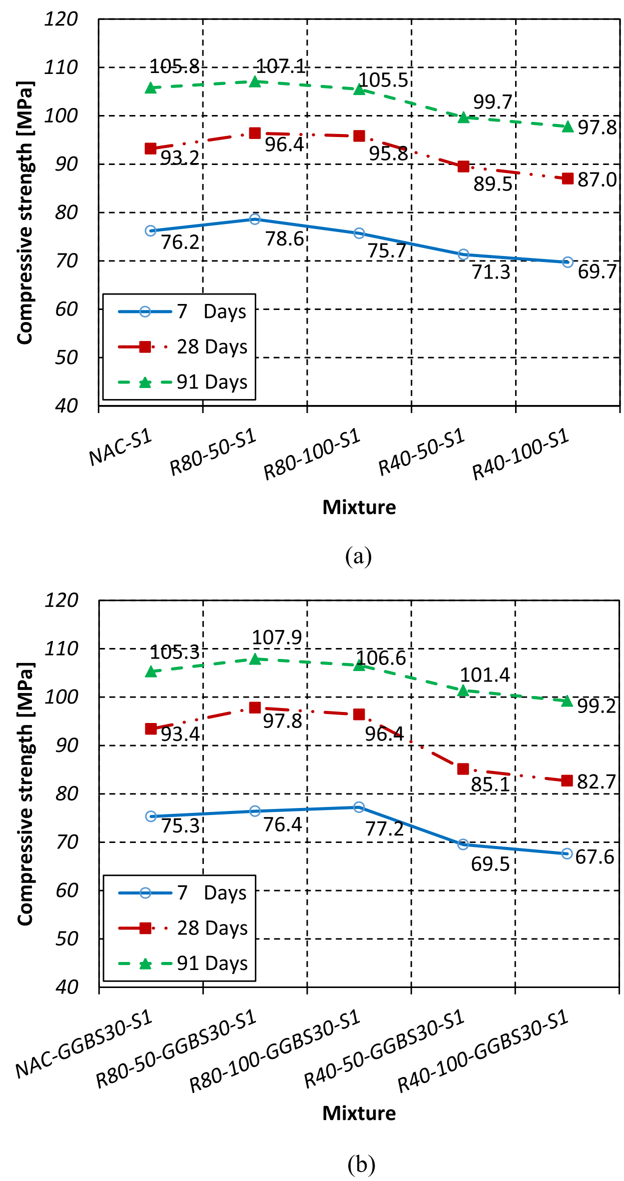


Fig. 3. Compressive strength of fiber-reinforced recycled aggregate concretes containing: (a) 0% GGBS and (b) 30% GGBS.

[53]. In a study conducted by Sharma and Pandey [55], the XRD pattern of 90-day hydrated sample of OPC mix blended with GGBS indicated higher reactivity of GGBS at this age compared to those of early ages. Therefore, slight reduction in the early age strengths were observed in the present study can be attributed to the lower hydration rate of concretes incorporating GGBS, which has been well documented in the literature [55,56]. On the other hand, Yang et al. [57] reported that substituting cement with GGBS at replacement ratio lower than 60% can lead to improvement in both early and long-term aging, owing to the greater activation energy and proportion of C-S-H. Fig. 3 shows that introducing 1% DHE steel fibers into concrete led to an enhancement in the compressive strength of concrete mixes at all ages. For instance, the compressive strength of NAC containing 1% steel fibers increased by 7%, 10%, and 16% at 7, 28, and 91 days of curing, respectively compared to those of the corresponding mix without fibers. DHE steel fibers, owing to their high elastic modulus and particular shape that restricts the propagation of cracks, alters the tendency of cracks, and subsequently improves the compressive strength of concrete

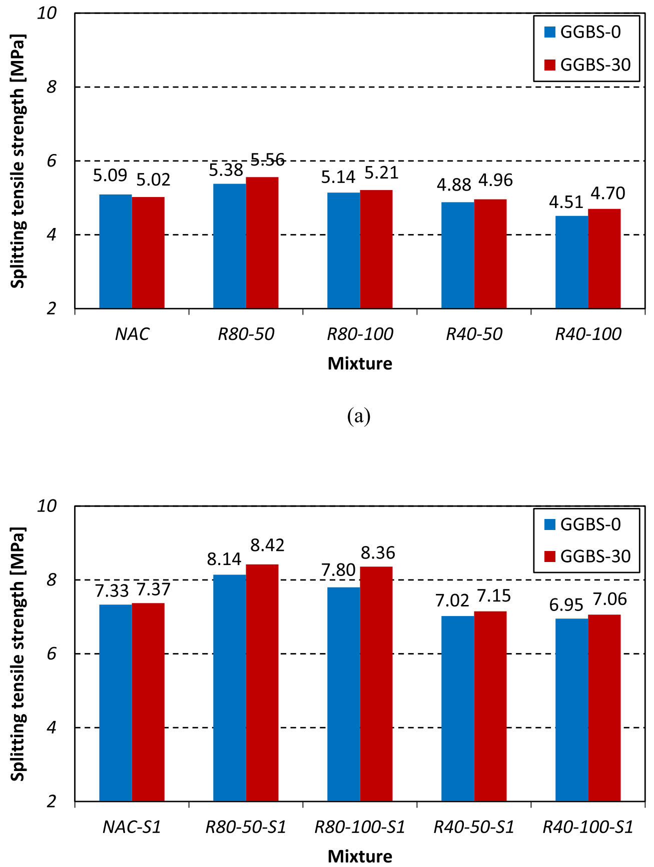


Fig. 4. 28-day splitting tensile strength of recycled aggregate concretes containing: (a) 0% steel fiber and (b) 1% steel fiber.

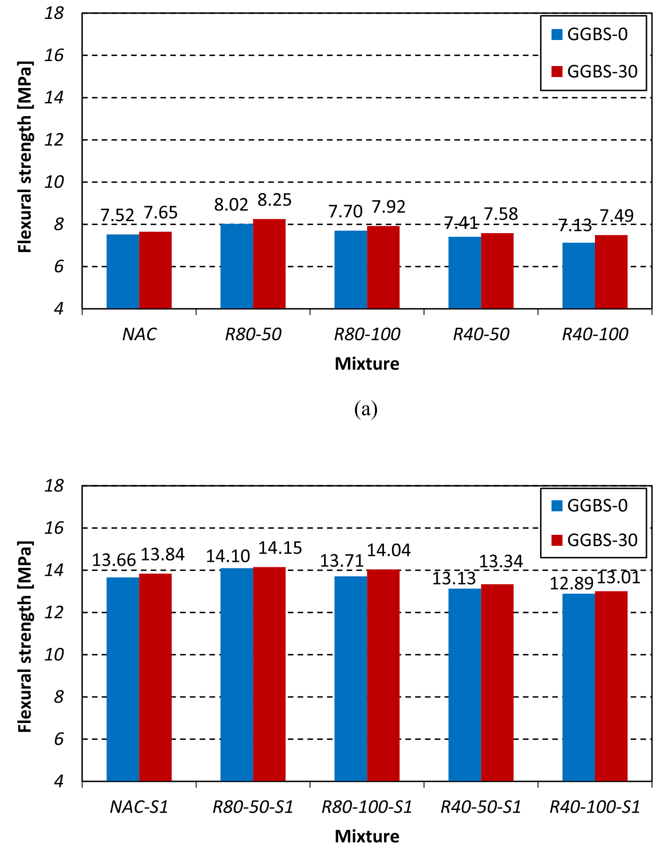


Fig. 5. 28-day flexural strength of recycled aggregate concretes containing: (a) 0% steel fiber and (b) 1% steel fiber.

[58]. The increase in the compressive strength of recycled aggregate concretes containing steel fibers varied from 3% to 14% compared to that of NAC, depending on the content and grade of RCA. Compressive strengths of recycled aggregate concretes containing steel fibers and GGBS were slightly lower at 7 and 28 days than those of the corresponding mixes without GGBS, whereas their 91-day strengths were equal or slightly higher.

Generally, the rate of strength development in concretes containing recycled aggregates, especially 40 MPa RCA, was higher than that of NAC. For instance, the 91 days compressive strength of NAC, R40-100, and R80-100 mixes were 28%, 38%, and 31% higher than their 7 days strength, respectively. This improvement can be explained by the development of an additional C-S-H that resulted from the internal water curing of the attached mortar on RCA, which has been shown to lead to an enhancement in the microstructure of the concrete [59,60]. This is in a good agreement with the findings of previous studies that showed that recycled aggregate concretes exhibit higher strength gain at a prolonged curing time than conventional concretes, as a result of improved ITZ, and densification of cement matrix [61,62].

3.2. Splitting tensile and flexural strengths

The 28-day splitting tensile and flexural strengths of the different mixes prepared in this study are shown in Figs. 4 and 5. The results show that the addition of 80 MPa RCA into concrete led to an increase in both the splitting tensile and flexural strengths of the concrete, whereas the use of 40 MPa RCA caused a reduction in both strengths of the concrete. For instance, the splitting tensile strength of the concrete containing 50% and 100% 80 MPa RCA increased by 6% and 1%, respectively, compared to that of the NAC. On the other hand, the splitting tensile strength of the concretes incorporating 50% and 100% 40 MPa RCA was 4% and 11% lower than that of the NAC, respectively. The enhanced splitting tensile and flexural strengths of 80 MPa RCA mixes can be explained by the improved bond strength at the interface between the old and new cement paste [63]. Additionally, the higher quality of 80 MPa RCA and its contribution to the formation of the secondary C-S-H are other contributing factors to the improved strengths. The physical properties of RCA like its rough surface might also further improve the microstructure of the ITZ, and subsequently increase the splitting tensile and flexural strength of concrete [64]. The reduced strengths of the concretes manufactured with 40 MPa RCA can be attributed to the excessive amounts of porous mortar adhered on the surface of RCA. The results indicate that, an increase in the replacement ratio of RCA from 50% to 100% led to a slight reduction in the strengths.

The results show that the replacement of OPC with 30% GGBS had only a minor influence on the splitting and flexural strengths of NAC. Nevertheless, a slight increase in the strengths of recycled aggregate concretes was observed with the inclusion of GGBS. For instance, as can be seen in Fig. 4, the splitting tensile strength of R80-50 and R80-100 series mixes increased by 9% and 2%, respectively, by the inclusion of GGBS. The flexural strengths of the mentioned mixes were 10% and 5% higher than that of the plain concrete, respectively. This increased strength can be explained by the ability of the fine GGBS particles to penetrate inside the

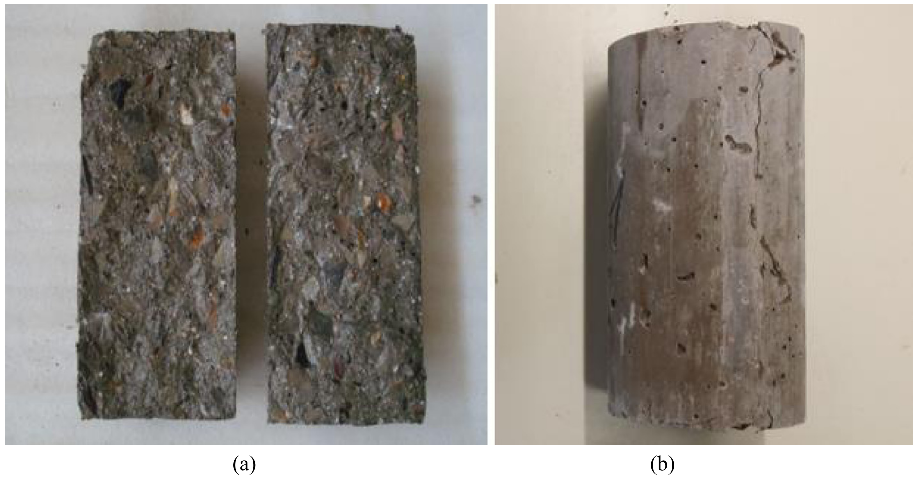


Fig. 6. Failure mode of HPC under splitting tensile load: (a) 0% DHE steel fiber and (b) 1% DHE steel fiber.

pores of RCA, enhancing the features of ITZ and bond between aggregates and cement matrix [65].

As expected, the addition of 1% DHE steel fibers significantly increased the splitting tensile and flexural strengths of all the mixes. It can be seen in Figs. 4 and 5 that splitting tensile and flexural strengths of NAC containing steel fibers increased by 44% and 82%, respectively. Similarly, Yoo et al. [66] reported that the inclusion of hooked-end steel fibers at a volume fraction of 1% or higher leads to significant improvements in both flexural strength and post-peak ductility of high-strength concrete. The results also demonstrate that the steel fibers were also very effective in improving the strengths of recycled aggregate concretes. For example, the increase in the splitting tensile strength of recycled aggregate concretes containing fibers ranged from 37% to 60%, while an increase of up to 88% was attained in the flexural strength, depending on the content and type of RCA. This improvement is attributed to the high tensile strength, elastic modulus, and effective anchoring mechanism of DHE steel fibers, which restrained the extension of macro-cracks in concrete. Carnerio et al. [67] also showed an increase of up to 26% and 36%, respectively, in the splitting tensile and flexural strength of recycled aggregate concretes reinforced with 0.75% hooked-end steel fibers. DHE steel fibers used in the present study exhibited significantly higher maximum pull-out forces compared to those of hooked-end steel fibers [68]. As a result, greater improvements in the splitting tensile and flexural strengths of concrete mixes were attained in this study compared to those reported in previous studies, in which conventional hooked-end steel fibers were used. As can be seen in Figs. 4 and 5, the presence of steel fibers resulted in a more significant improvement on the splitting tensile strength of recycled aggregate concretes compared to that of NAC. For instance, the splitting tensile strength of mixes R40-100-S1 and R80-100-S1 increased by 54% and 52%, respectively, over that of the corresponding mixes without fibers, whereas the inclusion of fibers in NAC mix led to an increase of up to 44%. This can be attributed to the better bond between RCA and paste due to the rough surface of RCA, and the interlocking effect between the fibers and RCA [69]. The results indicate that among different mixes considered in this study, the best performing mix was R80-50-GGBS30-S1 that achieved splitting tensile and flexural strengths of 8.42 and 14.15 MPa, respectively (compared to 5.09 and 7.52 MPa of NAC mix). The failure mode of plain concrete and concrete reinforced with 1% DHE steel fibers under splitting tensile load is shown in Fig. 6. As can be seen, the plain concrete was split into two parts, whereas this was prevented in the sample containing 1% DHE steel fibers, in which the fibers restrained the propagation of macro-cracks, and a longitudinal crack occurred only on the surface of concrete.

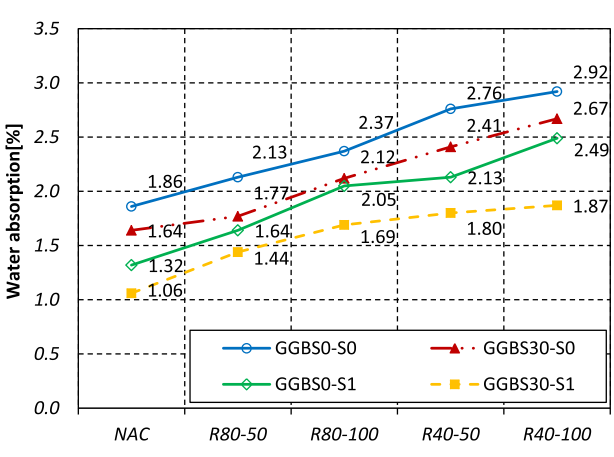


Fig. 7. Water absorption by immersion of recycled aggregate concretes obtained at 28 days.

3.3. Water absorption

The water absorption test results of the recycled aggregate concretes with or without GGBS and steel fibers are shown in Fig. 7. As can be seen in Fig. 7, the replacement of NA with RCA resulted in an increase in the water absorption of concrete. This figure also illustrates that there is a strong correlation between the water absorption and the strength of the parent concrete and RCA content. For instance, the replacement of 100% of NA with 40 MPa and 80 MPa RCA resulted in an increase of up to 57% and 27% in the water absorption, respectively. This can be explained by the higher porosity of RCA that originates from the attached mortar, and this was higher in the case of 40 MPa RCAs than 80 MPa RCAs. An increase in the water absorption of up to 14.2% [70], 17.5% [71], 62% [72], and 68.9% [73] was reported previously with the full replacement of coarse NA with RCA.

The results show that inclusion of GGBS resulted in a reduction in the water absorption. As can be seen in Fig. 7, the water absorption of NAC with GGBS was 12% lower over than that of the companion mix without GGBS. A reduction up to 17% was also observed in the water absorption of R80-50-GGBS30 mix compared to that of the corresponding concrete without GGBS. This reduction can be attributed to the ability of GGBS to improve the microstructure of cement matrix, decreasing the pores size, and interrupting the connection of pores [18]. In addition to the pozzolanic activity of GGBS, its filler effect might have also contributed to the reduction of water absorption owing to the small particle size of GGBS. As a result, GGBS might have penetrated into the pores of RCA, filling the cracks originally present in the RCA with its hydration product, and subsequently reducing the water absorption of concrete [40].

The results of recycled aggregate concretes reinforced with steel fibers illustrate that the inclusion of fibers had a significant effect on the water absorption of the concrete. It can be seen that the water absorption of NAC reduced by 29% by the inclusion of 1% steel fibers. Likewise, the water absorption of recycled aggregate concretes containing steel fibers was up to 23% lower than that of the corresponding mixes without fibers. These results suggest that the inclusion of fibers restrict the formation and propagation of cracks in the body of concrete leading to a reduced permeability [74]. As can be seen in Fig. 7, the influence of steel fibers was greater than that of the GGBS on the reduction of the water absorption. The results also indicate that the lowest water absorption was attained by the NAC-GGBS30-S1 mix, which showed a 43% reduction in water absorption over that of the companion plain concrete mix. Irrespective of the RCA content and type, the water absorption of the recycled aggregate concretes incorporating GGBS and steel fibers was lower than that of the NAC. These observations indicate that with the inclusion of GGBS and fibers HPC incorporating RCA can be designed to have a relatively low water absorption matching that of companion NAC.

3.4. Specific electrical resistivity

The resistance of reinforcing bars inside concrete to corrosion can be assessed through different tests. The electrical resistivity test is a non-destructive technique that allows the evaluation of the risk of corrosion according to available classifications [58]. It was recommended that an electrical resistivity of higher than 120 Ω m, between 50 and 120 Ω m, and lower than 50 Ω m, could be used to respectively represent the following probabilities for rebar corrosion: not probable, probable, and inevitable. The electrical resistivity test results of different recycled aggregate concretes are shown in Fig. 8 at three different testing ages (i.e. 7, 28, and 91 days). The results indicate that irrespective of the content and type of the recycled aggregates, the replacement of NA with RCA led to a reduction in the electrical resistivity of concrete at all testing ages. Furthermore, due to the lower quality and higher porosity of 40 MPa RCA over that of the 80 MPa RCA, concretes containing former ones showed lower electrical resistivity. It can also be seen in Fig. 8 that an increase in the RCA content caused a reduction in the electrical resistivity. This can be explained by the porous nature of recycled aggregates that provides ions with an easier condition to migrate into the concrete, which increases the possibility of rebar corrosion [75]. Also, the higher amount of water

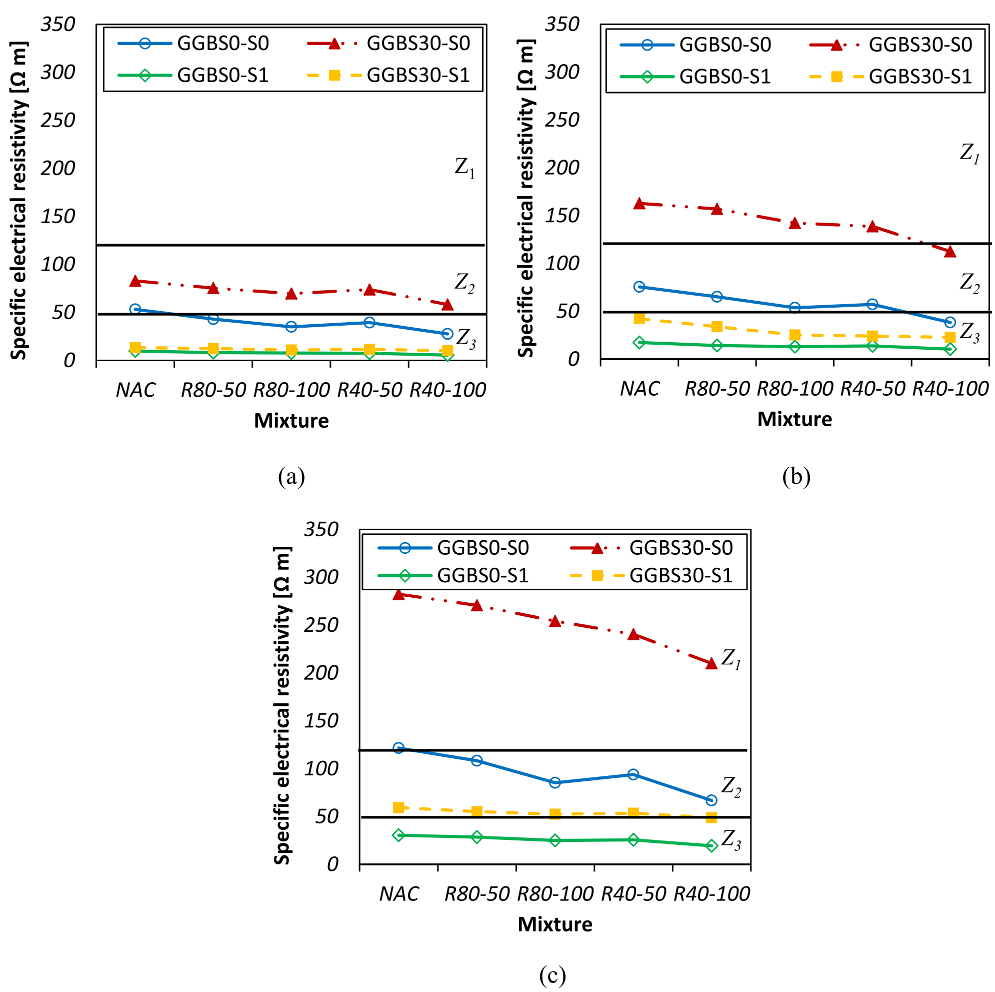


Fig. 8. Specific electrical resistivity of different recycled aggregate concretes at the ages of: (a) 7 days, (b) 28 days, and (c) 91 days (Z_1, Z_2, and Z_3 represent the following probabilities for rebar corrosion, respectively: not probable, probable, and inevitable [58]).

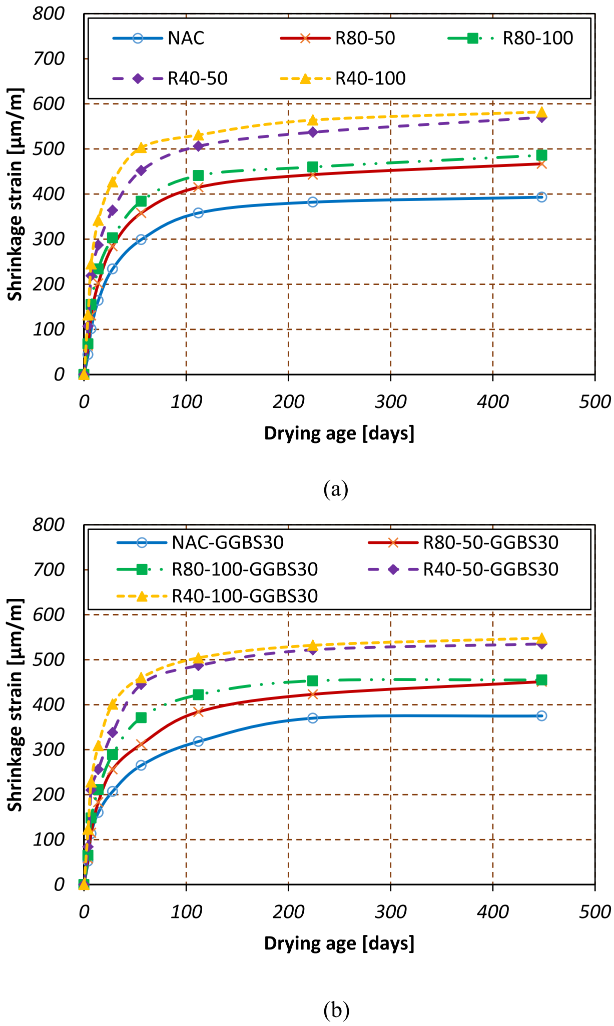


Fig. 9. Shrinkage under drying condition of recycled aggregate concretes containing: (a) 0% GGBS and (b) 30% GGBS.

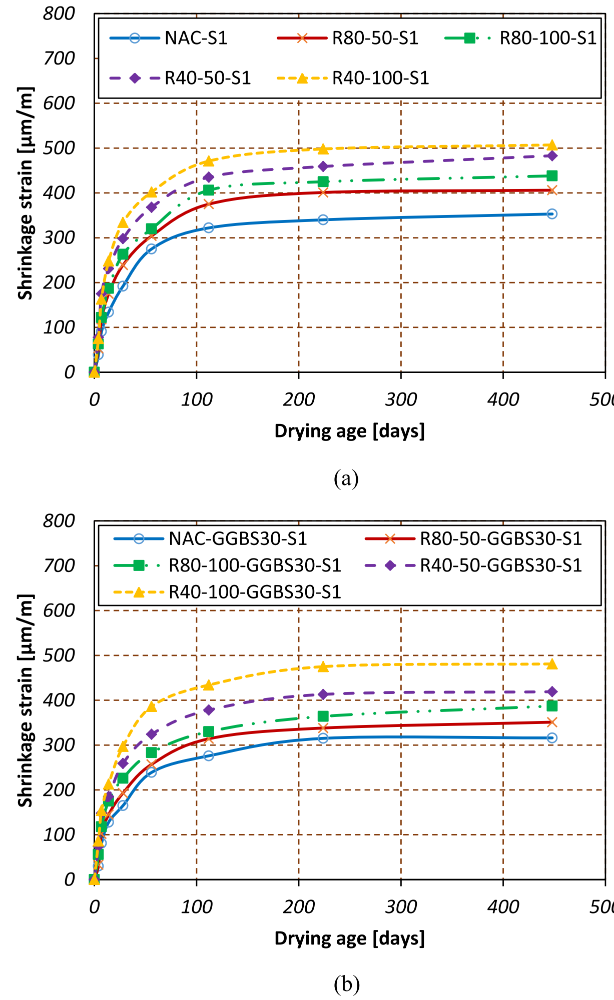


Fig. 10. Shrinkage under drying condition of fiber-reinforced recycled aggregate concretes containing: (a) 0% GGBS and (b) 30% GGBS.

inside the RCA, resulting from their higher porosity, creates an environment that increases the probability of steel rebar corrosion in concrete [75]. Similar observations on the reduction in the electrical resistivity of concretes incorporating RCA were reported previously [75,76]. As can be seen in Fig. 8, the reduction in the electrical resistivity of the recycled aggregate concretes varied from 11% to 49%, depending on the content and type of RCA, and testing age. The results also show that with the curing age the electrical resistivity of recycled aggregate concretes increased somewhat more significantly than that of NAC. For instance, the 91-day specific electrical resistivity of R40-50 and R80-50 mixes were 138% and 151% higher than the 7-day values, respectively, whereas this increase was 128% for NAC mix. This can be attributed to the previously discussed influence of the internal water curing and formation of additional C-S-H that improves the microstructure of concrete and reduces the capillary pores [8].

As can be seen in Fig. 8, the inclusion of GGBS in concrete significantly improved the electrical resistivity of concrete. The results show that GGBS inclusion significantly increased the electrical resistivity, especially at later ages of curing (i.e. 28 and 90 days). For instance, the specific electrical resistance of NAC incorporating GGBS were 56%, 115%, and 132% higher than that of the plain concrete at 7, 28, and 91 days, respectively. GGBS owing to its pozzolanic activity takes part in the development of secondary C-S-H gel, improves the microstructure of concrete and consequently interrupts the migration of ions [77]. The C-S-H gel, which is known as a source of strength in concrete, increases the volume of solid phases and reduces the formation of capillary pore systems in concrete. These phenomena result in an improvement in durability properties of concrete, such as its electrical resistivity [58]. The results of recycled aggregate concretes made with GGBS show that all of these samples achieved higher electrical resistance compared to that of the control concrete. The increase in their electrical resistivity varied from 9% to 123%, depending on the content and type of RCA and testing age.

The results of the concretes with steel fibers show a significant drop in the electrical resistivity. As can be seen in Fig. 8, fiber-reinforced concretes attained lowest electrical resistivity among all mixes investigated in this study. For instance, the electrical resistance of R40-100-S1 mix were 89%, 86%, and 84% lower over that of the NAC at 7, 28, and 91 days, respectively. This is due to the conductivity of steel fibers that drastically reduce the electrical resistance of concrete. According to the classification presented in Fig. 8, the corrosion of steel rebars in concretes produced in series A, B, C, and D would be probable, not probable, inevitable, and inevitable, respectively, at 28 days. The practical application of conventional SFRC subjected to marine environmental conditions has been limited due to the corrosion of steel fibers [78]. Frazão et al. [79] studied the durability of steel fiber-reinforced concretes by using rapid migration test and found that a slight increase in the chloride diffusivity of this mix occurred compared to that of the plain concrete. The growth of chloride ions in the fiber-paste interface weakened the protective oxide film of the steel fibers and subsequently increased the vulnerability of corrosion. Similarly, Afroughsabet et al. [58] reported that the inclusion of steel fibers in concrete led to a slight increase in the chloride diffusivity of FRC over that of the conventional concrete, which subsequently resulted in a reduction in the serviceability of FRC structures. It was observed that recently developed amorphous metallic fibers had higher corrosion resistance [78] due to their particular composition, and they showed no corrosion when immersed in HCl (0.1 N) and FeCl3 (0.4 N) for 24 h [80].

3.5. Shrinkage under drying condition

The results of the shrinkage tests under drying condition are shown in Figs. 9 and 10. The relative shrinkage of the recycled aggregate concretes at concrete ages of 56 and 448 days compared to that of the reference NAC mix is also shown in Fig. 11. The results indicate that mixes with recycled aggregates, irrespective of the parent concrete strength, exhibited a higher shrinkage strain compared to NAC mix. As can be seen in Fig. 9, the replacement of NA with RCA derived from a lower grade parent concrete and at a higher content led to the highest shrinkage strains. Clearly, the negative effect of RCA on the shrinkage of concrete was lower when NA was replaced with 80 MPa RCA. These results are in agreement with previous research on HPC containing RCA [81,82]. Similarly, Gonzalez-Corominas and Etxeberria [9] reported that the highest drying shrinkage occurred in concretes containing the highest RCA replacement ratios and lowest RCA qualities. The drying shrinkage strain of concrete has a direct relationship with the amount of free water and the porosity of concrete. Generally, the drying shrinkage occurs when the free water stored in the capillary pores evaporates due to a low relative-humidity environment. This circumstance leads to a humidity gradient which induces the transport of water particles from the C-S-H to the capillary pores after which it evaporates [9]. The higher amount of free water in the capillary pores and higher porosity of recycled aggregate concretes facilitate the transport of water and consequently increases the drying shrinkage strain. As can be seen in Fig. 11, the shrinkage strain of recycled aggregate concretes at 56 days and 448 days were 20–68% and 19–48% higher than those of the NAC, respectively, depending on the replacement level and type of RCA. These results indicate that the adverse effect of recycled aggregates on the shrinkage of concrete was slightly mitigated by increasing age of the concrete.

As can be seen in Fig. 11(a), the replacement of OPC with 30% GGBS led to a reduction in the shrinkage strain of concrete up to 11% over that of the plain concrete at 56 days. This result agrees with the finding of previous research [83,84]. The same trend was also evident in the recycled aggregate concretes and the mixes

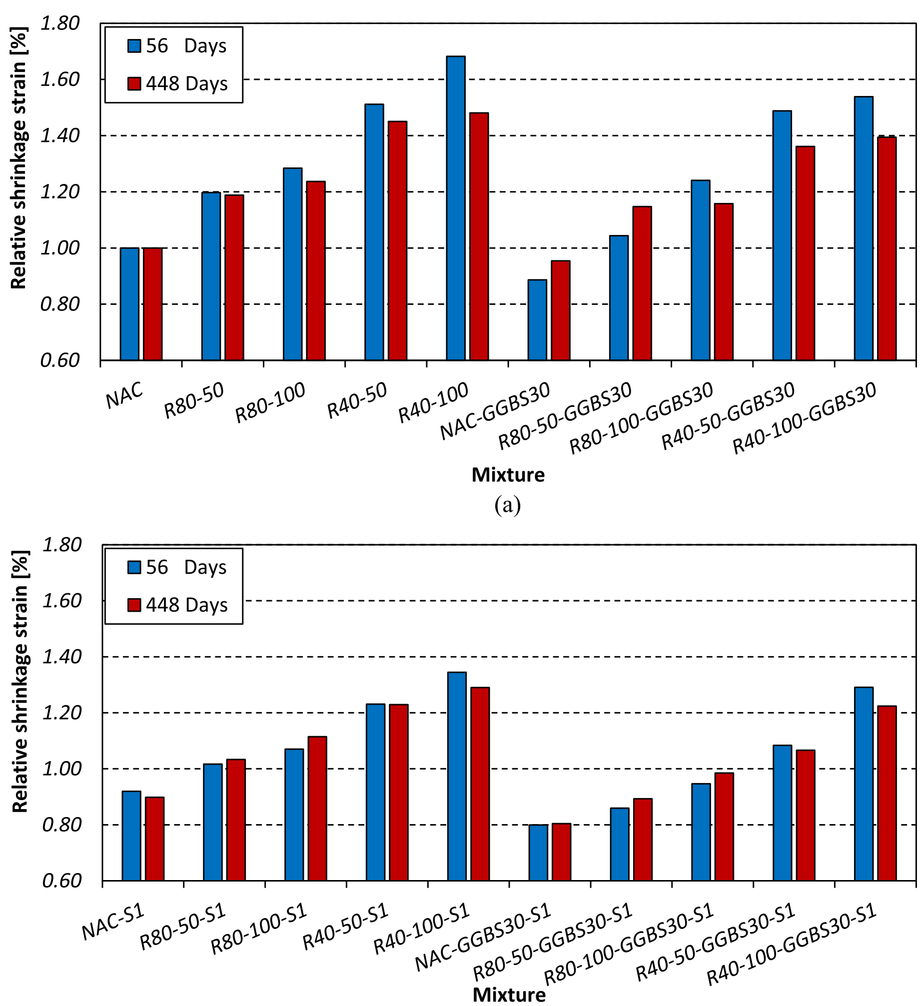


Fig. 11. Relative shrinkage under drying condition of recycled aggregate concretes containing: (a) 0% steel fiber and (b) 1% steel fiber.

incorporating of GGBS developed a lower shrinkage strain compared to the corresponding mixes without GGBS. This reduction in the shrinkage strain can be explained by the ability of GGBS to further promote the formation of ettringite and C-S-H at later ages, consequently leading to a denser material with reduced porosity [85].

The results show that the incorporation of steel fibers in concrete led to a reduction in the shrinkage strain. This result is in good agreement with previous research that showed that the fibers can arrest propagation of cracking produced as a result of drying shrinkage [86,87]. As can be seen in Fig. 11, DHE steel fibers were slightly more effective in reducing the shrinkage of recycled aggregate concretes than that of NAC. For instance, a reduction of 10% in 448 days shrinkage of NAC reinforced with steel fibers was achieved, while the reduction in the recycled aggregate concretes containing fibers was up to 15%. As can be seen in Fig. 11, the lowest shrinkage strain was obtained by the NAC containing GGBS and steel fibers, whereas the maximum strain was developed by the mix containing 40 MPa RCA at 100% replacement.

4. Conclusions

This paper studied the effect of DHE steel fibers and GGBS on the mechanical and durability properties of HPC containing recycled aggregates of different grades and contents. The following conclusions can be drawn from the experimental results:

1. The strength of HPC containing RCA depends on the strength and quality of the parent concrete RCA is obtained from. Using 80 MPa RCA, HPC with matching mechanical properties to NAC can be produced. However, the use of RCA with a lower parent concrete strength reduces the strength of the concrete. Full replacement of NA with RCA results in a slight reduction in the strength of concrete compared to corresponding mixes with 50% RCA.
2. Irrespective of the content and type of recycled aggregates, the use of RCA in HPC adversely affects the durability properties of concrete. Full replacement of NA with 100% of 40 MPa RCA resulted in 57% and 68% increase in the water absorption and shrinkage, respectively, and a 49% decrease in the electrical resistivity of concrete.
3. With the curing age the electrical resistivity of recycled aggregate concretes increases more significantly than that of NAC. Mixes with 50% of 40 MPa and 80 MPa RCA experienced a 138% and 151% increase in their electrical resistivity between 7 and 91 days, respectively, whereas this increase was 128% for NAC mix. This can be attributed to the formation of additional C-S-H as a result of internal water curing that improves the microstructure of concrete and reduces the capillary pores.
4. The replacement of OPC with 30% GGBS in concrete has a slight influence on the strength of concrete, and HPC containing GGBS exhibits similar strengths to those of concrete with 100% OPC. On the other hand, the inclusion of GGBS leads to a decrease in the water absorption and shrinkage of concrete, and significantly increases the electrical resistivity of concrete. The positive influence of GGBS becomes more pronounced at later ages of curing.
5. The effect of GGBS in the improvement of the properties of recycled aggregate concretes is relatively higher compared its effect in NAC. This can be explained by the ability of the fine GGBS particles to penetrate inside the pores of RCA, enhancing the features of ITZ and bond between aggregates and cement matrix.
6. The addition of DHE steel fibers to recycled aggregate concretes at a fiber volume content of 1% led to an up to 60% increase in the splitting tensile strength and up to 88% increase in the flexural strength at 28 days.
7. With the addition of steel fibers the water absorption, shrinkage, and electrical resistivity of NAC decreased by 29%, 10%, and 77%, respectively at 28 days. This reduction was up to 23%, 15%, and 86% in recycled aggregate concretes, respectively.

The results indicate that it is possible to develop sustainable HPC with mechanical and durability properties matching those of NAC through the use of RCA obtained from high grade parent concrete together with GGBS and DHE steel fibers. These findings are very promising, and are pointing to the possibility of significantly reducing the environmental impact of HPC without any reduction in performance.

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