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MECHANICAL PROPERTIES OF RECYCLED COARSE AGGREGATE CONCRETE REINFORCED WITH STEEL FIBERS

NANCY KACHOUH, HILAL EL-HASSAN, and TAMER EL-MAADDAWY

Dept of Civil and Environmental Engineering, UAE University, Al Ain, UAE

This paper presents the combined influence of natural aggregates (NA) replacement with recycled concrete aggregates (RCA) and incorporating steel fiber reinforcement on the mechanical properties of normal-strength (30 MPa) concrete mixes. Hooked-end steel fibers were added in a 2% volumetric fraction to promote 100% RCA replacement. Fine aggregates were in the form of locally-abundant desert dune sand. Mechanical properties of 28-day concrete samples were assessed, including compression strength, tensile splitting strength, elastic modulus, flexural stress, and flexural toughness. For plain concrete mixes, the replacement of NA by RCA resulted in 18, 27, and 5% reductions in the respective design compression strength, elastic modulus, and tensile splitting strength. Nevertheless, the addition of steel fibers could restore the aforementioned properties by up to 90, 77, and 164%. Compared to the control mix made with NA, the flexural strength of the plain RCA-based concrete mix decreased by 33%, while the flexural toughness increased by 100%. In turn, the corresponding flexural properties of RCA concrete mix reinforced with steel fibers were 2 and 56 times those of the control made with NA. Findings provide evidence of the ability to produce concrete made with 100% RCA and reinforced with steel fibers with comparable compression properties and improved tensile and flexural performance compared to those of NA-based concrete.

Keywords: Recycled aggregate, Fiber reinforcement, Flexural performance, Compression behavior, Splitting tensile strength.

1 INTRODUCTION

After demolishing old concrete structures, waste concrete is typically disposed of in landfills, causing serious environmental hazards. Recycling such demolished concrete to produce recycled concrete aggregates (RCA) is a sustainable resolution to the problem of disposal of waste concrete. It also promises to minimize the utilization of natural aggregates (NA) in concrete production, one of the most industrially consumed construction products, and reduce its carbon footprint (Radonjanin *et al.* 2013, Alzard *et al.* 2021). Consequently, many studies have evaluated the possibility to replace NA with RCA in the production of structural concrete (Rao *et al.* 2007, Etxeberria *et al.* 2007, Wagih *et al.* 2013, Shoaib *et al.* 2021). The results showed that such replacement caused reductions in different physical, mechanical, and durability properties (Meyer 2009, de Juan and Gutiérrez 2009, Debieb *et al.* 2010, Kachouh *et al.* 2019a). The deteriorated performance attributed to the use of RCA was mainly caused by the old mortar adhered to the RCA, which created a weak interfacial zone with the new binder paste (Thomas *et al.* 2018, Guo *et al.* 2020). Nevertheless, researchers investigated different methods to improve the RCA concrete performance, including the use of more cement, lowering the water-to-cement ratio, adding pozzolans and supplementary cementitious materials, detaching or enhancing the strength of the old mortar adhered to the RCA, and incorporating steel fibers (SF) (Tabsh and Abdelfatah 2009, Malešev *et al*. 2010, Corinaldesi 2010, Radonjanin *et al*. 2013, Kachouh *et al*. 2019a, Gao *et al*. 2017, Kachouh *et al*. 2019b, Carneiro *et al*. 2014, Bencardino *et al*. 2010, Kachouh *et al*. 2020). Of these methods, reinforcing RCA concrete with steel fibers was found to be the most promising construction material with its ability to enhance the sustainability aspect of concrete while meeting the structural and environmental requirements.

Based on the conducted literature review, several research studies have examined the properties of concrete made with RCA and reinforced with steel fibers. Yet, the compression, tensile, and flexural properties of such concrete have not been collectively assessed. Accordingly, this research aims to evaluate the impact of incorporating steel fibers on the performance of concrete made with 100% RCA, including the concrete compression strength, elastic modulus, tensile splitting strength, flexural stress, and flexural toughness.

2 MATERIALS AND METHODS

2.1 Materials

Ordinary Portland cement (OPC) was employed as the binding material in all concrete mixes. Coarse aggregates were in the form of RCA and NA. The RCA was obtained from a recycling facility that quashes and sieves concrete from old structures. Conversely, the NA was crushed dolomitic limestone. The respective maximum particle size of RCA and NA were 19 and 25 mm. Their gradation curves were within the limits of ASTM C33. Also, both aggregates were utilized in saturated surface dry condition. Desert dune sand was employed as the fine aggregates. The properties of the aggregates are presented in Table 1. The SF were hooked at both ends with mean diameters and lengths of 0.55 and 35 mm, respectively. Their respective tensile stress and Young's modulus were 1345 and 210000 MPa.

Table 1. Physical properties of NA, RCA, and dune sand.

Property	ASTM	NA	RCA	Dune Sand
Unit Weight (kg/m^3)	C29	1635	1563	1663
Specific gravity	C127	2.82	2.63	2.77
Specific surface area (cm^2/g)	C136	2.49	2.50	116.80
Water absorption (%)	C127	0.22	6.63	-
Fineness modulus	C136	2.46	2.53	2.42

Table 2. Concrete mixture proportioning (in kg/m^3).

Mix No.	Mix Designation	Cement	NA	RCA	Dune sand	Water	Steel fibers
1	R000SF0	470	1130	0	570	230	0
2	R100SF0	470	0	1130	570	230	0
3	R100SF2	470	0	1130	570	230	156

2.2 Mixture Proportioning

The control mix was designed and prepared following ACI 211.1 to achieve a concrete cylinder compressive stress (f'_c) of 30 MPa. The mixture proportions of the three concrete mixes are presented in Table 2. Mixes were labeled RXXXSFY, where XXX denoted the RCA replacement percentage, by mass, and Y indicated the SF volume fraction (v_f). The total amount of cement, water, coarse aggregates, and dune sand were unchanged in all mixtures. Replacement of NA by RCA was taken as 0 and 100%, while SF v_f was selected as 0 and 2%.

2.3 Sample Preparation

Concrete mix constituents were mixed in a motorized shear mixer in the laboratory. For the mix incorporating SF, a special mixing procedure was employed. First, the SF were mixed with the coarse aggregates for 3 min to guarantee uniform dispersion. Then, the dune sand and cement were incorporated and homogenized with the other components by mixing for 2 more min. Finally, water was steadily added and mixed for another 2 min. This mixing procedure ensured a uniform and homogenous mixture. Freshly prepared concrete was cast in cylinders and prisms and compacted on a vibrating table to assure proper compaction according to ASTM C192. After 24 h, samples were removed from the molds and water cured in a tank at 23±2°C until testing after 28 days. For each mix, three replicate samples were prepared per test to obtain an average.

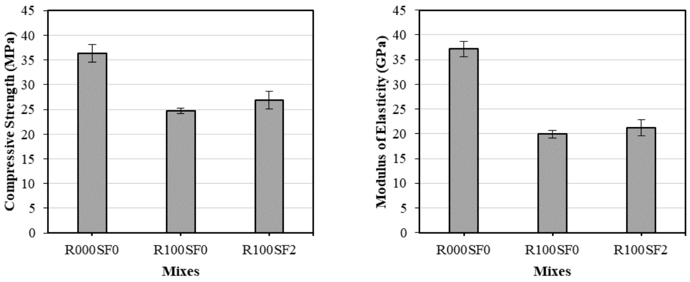
2.4 Performance Evaluation

To evaluate the cylinder compressive strength (f'_c) and modulus of elasticity (E_c), tests were performed on 28-day 100 mm x 200 mm (diameter x height) cylinders as per ASTM C39 and ASTM C469, respectively. Furthermore, flexural tests were conducted on 28-day prismatic specimens of dimensions 100 mm x 100 mm x 500 mm (width, height, and length) according to the procedure of ASTM C1609. The splitting tensile strength (f_{sp}) was carried out on 150 mm diameter and 300 mm length cylindrical specimens as per ASTM C496.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Compression Behavior

3.1.1 *Compressive strength*



(a) (b)

Figure 1. Compression behavior of concrete mixes: (a) Compressive strength; (b) Modulus of elasticity.

The 28-day compressive strength (f'_c) of concrete mixes is shown in Figure 1-a. The variability in the results is represented by the error bars. Results showed that 100% replacement of NA by RCA decreased the compressive strength by 18% in comparison to the control mix. Such reduction is caused by the porous structure of RCA, presence of micro-cracks in the old mortar, and weak interfacial zone between the new cement paste and old mortar adhered to the RCA. While adding SF was not mainly intended to increase the compressive strength, the effect of their addition was studied. The compressive strength of the concrete mix incorporating 2% SF and 100% RCA was 90 and 108% of that of R000SF0 and R100SF0, respectively. This improvement in the compressive strength is attributed to the bridging effect of SF (Gao *et al.* 2017).

3.1.2 *Modulus of elasticity*

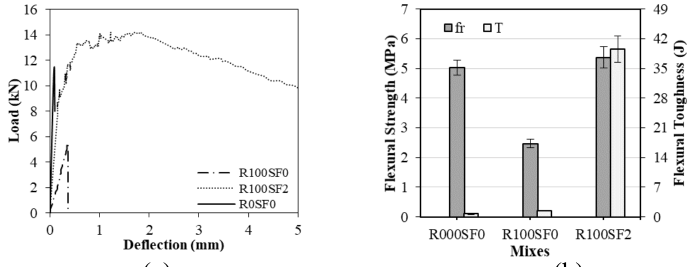
Figure 1-b illustrates the modulus of elasticity (E_c) of the different concrete mixes. In comparison to the control mix R000SF0, the mix made with 100% RCA had a 27% lower E_c, owing to the porous concrete structure caused by the presence of the old adhered mortar attached to RCA. Further, the addition of 2% SF volume fraction to the 100% RCA concrete mix led to a 7% increase in E_c over that of the plain RCA mix, but was 23% lower than that of the control mix R000SF0. This indicated an increase in concrete stiffness after adding SF.

3.2 Flexural Behavior

3.2.1 *Load-deflections curves*

The load-deflection curves of various concrete mixes obtained from the four-point flexural tests are illustrated in Figure 2-a. For concrete mixes R000SF0 and R100SF0, the load-deflection curves were characterized by a linear-elastic behavior up to the peak load followed by a sudden failure of the specimens and no post-peak response. It is worth noting that the slope of the pre-peak part of the curve of mix R100SF0 was smaller than that of mix R000SF0, owing to the lower modulus of elasticity. Furthermore, a comparison between the curves of R100SF0 and R100SF2 illustrates the effect of SF. While the load-deflection curve of R100SF0 was mainly one part, that of R100SF2 consisted of three parts. The first part corresponds to the pre-peak loading of the pre-cracked concrete specimen and is controlled by the modulus of elasticity. The second part is between the cracking and the peak load. It is characterized by an increase in load up to the peak load and is associated with the formation of mortar-aggregate interfacial micro-cracks and a dominant macrocrack. The third part of the R100SF2 curve relates to the post-peak softening phenomenon. It is depicted by a long tail that reflects the residual flexural strength of the specimen. Among the three mixes, R100SF2 is the only one to exhibit post-peak behavior.

3.2.2 *Flexural strength*



(a) (b)

Figure 2. Flexural behavior of mixes: (a) Load-deflection curves; (b) Flexural strength and toughness.

The flexural strength (f_r) of different concrete mixes is shown in Figure 2-b. Compared to the control mix R000SF0, concrete mix incorporating 100% RCA and no steel fibers exhibited a reduction in the peak strength by 33%. This reduction in strength is attributed to the inferior properties of RCA, the weak interfacial region between the new and old mortars, and the porous structure of RCA. The effect of adding SF on f_r was also evaluated. Compared to the mixes R100SF0 and R000SF0, adding 2% SF volume fraction to the concrete mix made with 100% RCA (R100SF2) led to an increase in the flexural strength by 117 and 50%, respectively. Apparently, the inclusion of SF improved the flexural performance and reduced the development of micro-cracks by providing concrete with better integrity due to its bridging effect.

3.2.3 *Flexural toughness*

The flexural toughness is an indication of the concrete's capacity to absorb energy. As per ASTM C1609, it is calculated as the area beneath the load-deflection curve to a deflection of 1/150 of the concrete prism's length. Figure 2-b displays the flexural toughness of the three mixes. The value for mix R000SF0 was 0.7 J, while that for R100SF0 and R100SF2 were 1.4 and 39.6 J, respectively. This represents a corresponding increase of 2 and 56 times. Thus, it is clear that a higher toughness was achieved with the addition of 2% SF, by volume, owing to their ability to bridge the cracks and delay their formation and propagation under flexural loading.

3.3 Splitting Tensile Strength

The splitting tensile strength of the three concrete mixes are depicted in Figure 3. Compared to the reference mix R000SF0, the complete replacement of NA with RCA reduced the splitting tensile strength by 5%. This decrease is in line with that reported in the flexural and compressive strength. Yet, the addition of SF to the mix made with 100% RCA resulted in a 72 and 64% increase compared to the respective plain counterparts R100SF0 and R000SF0. The SF bridging effect provided concrete with better resistance to tensile crack initiation and propagation.

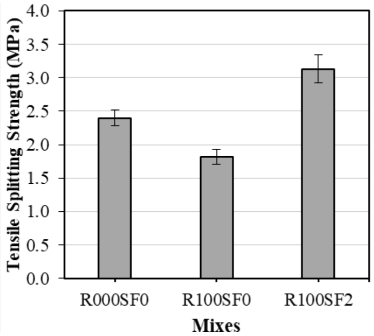


Figure 3. Splitting tensile strength of the examined concrete mixes.

4 CONCLUSIONS

This paper features the collective influence of RCA and SF on the mechanical properties of normal-strength (30 MPa) concrete. Based on the test results, the replacement of 100% of NA with RCA was found to lead to lower concrete compression strength, elastic modulus, flexural strength, and splitting tensile strength by 18, 27, 33, and 5%, respectively. This reduction is mainly caused by porous RCA structure and the weak interfacial area between the old adhered mortar and the new one. Compared to the control mix R000SF0, incorporating 2% SF volume fraction to the 100% RCA concrete mix restored up to 90, 77, 150, and 164% of these respective properties. Moreover, a 2- and 56-fold increase in flexural toughness was noted for R100SF0 and R100SF2 compared to that of R000SF0. This performance enhancement upon steel fiber inclusion was owed to their bridging effect and ability to mitigate crack formation and propagation. Future studies will evaluate the lifecycle assessment and economic feasibility of using such concrete in construction applications.

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