INFLUENCE OF STEEL FIBER ON MECHANICAL RESPONSE OF RECYCLED CONCRETE

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Abstract: The flexural response of conventional concrete material is known to be enhanced by incorporating a moderate volume-fraction of randomly distributed steel fibers. However, there is limited information on describing the influence of fiber volume-fraction on the compressive and flexural response of recycled coarse aggregate concrete (RCA-C) material. This paper reports on experimental test results of the RCA-C material formulated with 50% recycled aggregate replacement and 0 to 1.5% steel fiber volume fraction. Three-point flexural tests of notched prism specimens were completed. The mechanical properties in compression were characterized using cube specimens. Significant improvement in compressive and flexural strength of RCA-C was found as fiber content was increased from 0 to 1.5%. The experimental test results of RCA-C were further evaluated to investigate the influence of fiber content on flexural toughness. According to test results, the addition of steel fibers to RCA-C material appreciably increases the flexural toughness.

1 INTRODUCTION

The use of recycled coarse aggregate concrete in buildings and bridges has received significant attention over the recent years. However there has not been enough research to characterize the mechanical properties of this material in compression, flexure, and tension. Some standards prohibit the structural use of recycled coarse aggregate concrete, as the mechanical response of this type of concrete are not well established (Brazilian Association of Technical Standards ((ABNT), BCSJ 1977). However the British Standard Code allow to replace 20% of the total aggregate in the concrete with crushed aggregate (BS 8500-2). Likewise, the German code allows the use of 25% to 40% recycled aggregate as replacement. However aggregate size less than 2 mm are not allowed (DafStb-Richtlinie).

According to past research, compared to conventional concrete (CC), the recycled aggregates feature more porous texture, lower density, smaller modulus of elasticity, higher shrinkage and water absorption as well as reduced resistance to freezing and thawing (Kou and Poon 2013, Ajdukiewicz and Kliszczewicz 2002, Li 2008). According to Zaharieva et al. (2004), the response of RCA-C concrete material is primarily affected by the crushed aggregate material quality and quantity. Thus special care shall be taken to ensure a high quality crushed aggregate is used in the RCA-C material.

According to Li (2008) and Limbachiya et al. (2012), slight changes in the mechanical properties of RCA-C with 20% to 30% aggregate replacement were observed. However the higher recycled coarse aggregates content would significantly result in drop in the compressive strength of the RCA-C (Kwan et al 2012, Chakradhara Rao et al. 2011). This is most probably attributed to the increased porosity in the concrete texture and the weak transitional zone between the recycled aggregate and cement matrix (Xing and Zhou 1998).

The addition of steel fibers to CC and RCA-C is reported to enhance the mechanical properties of normal concrete in flexure, compression, tension, and shear. In addition the use of steel fiber would significantly improve the permeability of concrete by retarding the crack initiation and propagation rate. However no clear relationship is provided to quantify the influence of steel fibers.

A detailed understanding of the mechanical properties of Recycled Concrete is required to efficiently use its available capacity and satisfy the performance requirements of structural members. While numerous studies have investigated the compressive strength of this type of concrete, flexural strength and the role of volume-fraction of randomly distributed steel fibers on these properties has not been widely established. Thus, as series of cube and prism specimens were cast and tested in this research program to study the compressive and flexural response of steel fiber recycled concrete

2 EXPERIENTAL PROGRAM OVERVIWE

This study seeks to identify and analyze the mechanical response of the conventional concrete (CC) and recycled crushed aggregate concrete (RCA-C). Two levels of aggregate replacement, i.e., 0% and 50% along four different fiber volume fractions (V_f), of 0, 0.5, 1 to 1.5% were used in this research program. The experiments were completed at the ages of 7 days and 28 days using a total of 96 cubic samples (150x150x150 mm). The flexural tests of 48 prism samples beams with dimensions of 100x100x350 mm were also completed. The samples are cast and stored for 24 hours in humidity room, and then demolded and stored for 28 days at 23 °C in water reservoirs according to the ASTM standard.

2.1 Materials

2.1.1 Cement

Locally produced Type 2 Portland cement was used in both CC and RCA mixes, which had the best compatibility with other mix components.

2.1.2 Aggregates

Fine and coarse aggregates with a maximum size of 19 mm were obtained from the stockpiles of local uplier. The recycled aggregates (19 mm coarse aggregate and fine aggregate) were obtained from an existing 45-years-old concrete building.

2.1.3 Silica fume (SF)

The use of SF in concrete improves the mechanical properties in compression and flexure through pozzolanic activity and by filling voids between the cement grains. The use of SF also improves the rheological characteristics of the paste. An undensified SF was used in the current study, having manufacturer specified properties of: greater than 98.9% SiO_2; specific surface =18-20 m^2/g; maximum particle size =0.1 μm; bulk density = 250-300 kg/m^3.

2.1.4 Superplasticizer (SP)

Use of SP is required to obtain a mix with adequate workability. A polycarboxyl-based SP with density of 1.1±0.02 g/cm^3 and 30% solids content showed the best consistency for mix workability, and allowed the highest compressive strength among the SP and cement combinations considered in this study. Only mixes with this selected SP are presented in this paper.

2.1.5 Steel fibers

The distributed steel fibers provide an alternate force transfer path across the cracks, thus reducing the crack imitational and propagation and improving the aggregate interlock. Double-hooked steel fibers with length and diameter of 50 mm and 0.8 mm respectively and aspect ratio of 62.5 were used. The tensile strength of fiber was 1100 MPa.

2.2 Mixture preparation

In order to study the effect of recycled-aggregate replacement and fiber volume fraction on flexural and compressive strength of both conventional concrete (CC) and RCA-C material, a series of mix were cast. The mix compositions of each mix design are reported in Tables 2. The reference concrete mix, called CC, was prepared with 100% of natural aggregates with a maximum aggregate size of 19 mm. The RCA-C concrete was prepared with 50% recycled-aggregate substitution, called RC50. The maximum crushed aggregate size of 19 mm was selected. All the CC ad RCA-C concrete mixes were prepared with a water-to-cement ratio (w/c) of 0.36. The cement and Silica Fume content were 430 kg/m3 and 40 kg/m3 respectively. Four different volume fraction (V_f = 0, 0.5,1 and 1.5%) of hooked end steel fibers with a length of 50 mm, aspect ratio of 62.5 and yield strength of 1100 MPa were used. According to past research, volumes of fibers above 1.5% have been shown to have minimal strength improvements over mixes containing 1.0% and 1.5% fibers.

Table 2: Mix composition of Conventional and RCA-C concrete

Notation	R (%)	V_f, (%)	W kg/m^3	C kg/m^3	S kg/m^3	NCA kg/m^3	RCA kg/m^3
CC 0	0	0	150	430	888	815	0
CC 0.5	0	0.5	150	430	888	815	0
CC 1	0	1	150	430	888	815	0
CC 1.5	0	1.5	150	430	888	815	0
RCA-C 50-0	50	0	150	430	888	408	408
RCA-C 50-0.5	50	0.5	150	430	888	408	408
RCA-C 50-1	50	1	150	430	888	408	408
RCA-C 50-1.5	50	1.5	150	430	888	408	408

R: Replacement; V_f: Volume fraction; W: Water; C: Cement; S: Sand; NCA: Natural Coarse Aggregate; RCA-C: Recycled Coarse Aggregate

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Compression

The compressive strength of 150 mm cubes was determined according to ASTM C109 to understand the peak compressive strength. A minimum of three replicate tests of each samples are completed. The load rate applied to cubes was set at a rate of 0.5 MPa/s. The compressive load-strain response was investigated and it was observed that, regardless of fiber content, the stress-strain response is nearly linear until the peak compressive strength is reached. Unlike the plain mix (i.e., V_f = 0%) with a sudden drop in strength immediately after the peak, the mix incorporating 1.5% fiber volume-fraction exhibited a short region of hardening behavior followed immediately by a softening branch. The superior post-peak deformation capacity in mixes incorporation steel fibers is mainly attributed to the confinement effect provided by steel fibers.

3.1.1 Influence of fiber volume fraction on compressive strength

The influence of fiber volume-fraction on the peak compressive strength of conventional concrete (CC) and recycled coarse aggregate concrete (RCA-C) material is summarized in Table 3 and Figure 1 for 7-days and Figure 2 for 28-days. Compared to the plain RCA-C mix with V_f = 0%, the use of V_f = 0.5, 1, and 1.5% fiber was found to increase the compressive strength by 17%, 20%, and, and 26% respectively at the age of 7 days. See Figure 1(a). A similar trend was observed for the conventional concrete material, where the average peak strength was 13% higher than RCA-C mix with similar fiber content. See Figure 1(b).

The peak compressive strengths of CC and RCA-C material at the age of 28 days are presented in Figure 2. It was found that the no improvements in compressive strength at the age of 28 days were found after 0.5% and 1.0% fibers were respectively added to CC and RCA-C. However, the strain corresponding to peak compressive stress increases with an increase in fiber volume-fraction content.

Compared to conventional concrete, the RCA-C material tends to show a lower compressive strength at the age of 7 days. However higher peak compressive strength was found for RCA-C material at the age of 28 days except for mixes with 0.5% fiber content.

Table 3 – Compressive strength of concretes

Designation	Compressive strength, MPa		Gain from 7 to 28 days (%)
	7 days	28 days	
CC 0	34.5	51.6	49
CC 0.5	38.0	55.1	45
CC 1	36.90	50.0	36
CC 1.5	41.6	49.6	19
RCA-C 50-0	30.2	53.8	78
RCA-C 50-0.5	35.1	53.8	53
RCA-C 50-1	35.8	57.6	61
RCA-C 50-1.5	38.0	52.7	39

3.1.2 Influence of time development on compressive strength

The results of 7 and 28 days compressive strength test of cubic samples are summarized in Table 3 and Figure 1 and 2. The results indicates that the peak compressive strength of conventional concrete at the age of 28 days are 49%, 45%, 36%, and 19% higher than those at the age of 7 days for mixes with V_f = 0%, 0.5%, 1%, and 1.5% respectively. A similar trend was observed for the RCA-C material, where 78%, 53%, 61%, and 39% improvement in 28 days strength over the 7 days were found for mixes with V_f = 0%, 0.5%, 1%, and 1.5% respectively. See Figure 1 (a).

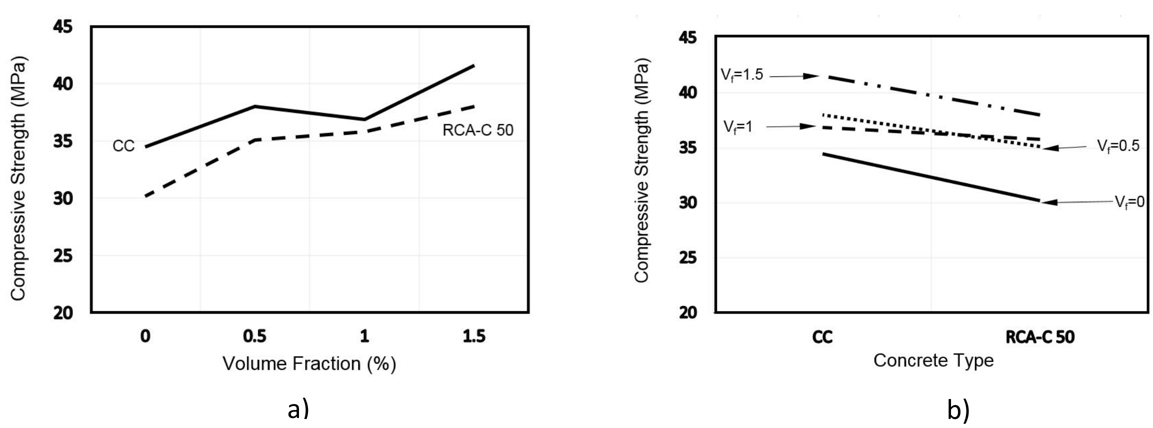

Figure 1. 7 days Compressive Strength: a) Volume Fraction, b) Concrete Type

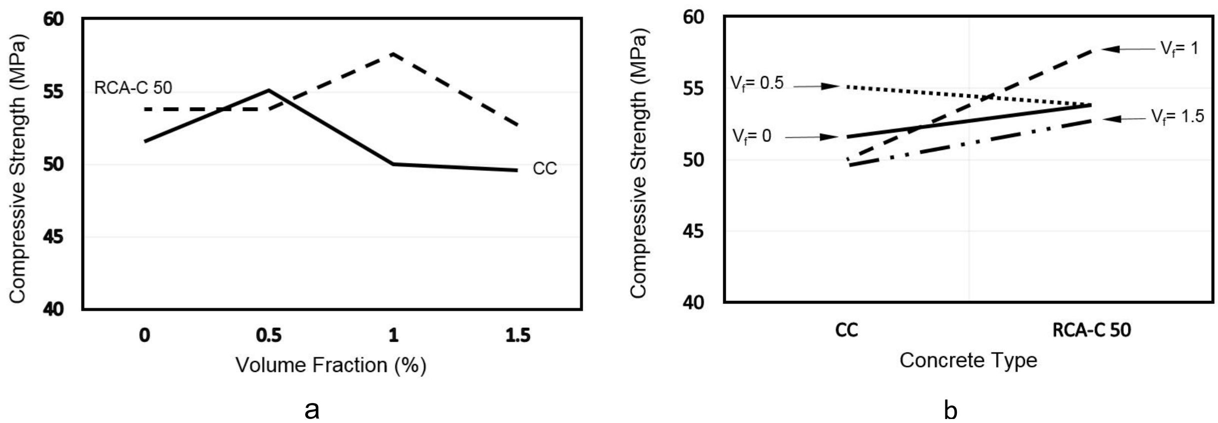

Figure 2. 28 days Compressive Strength: a) Volume Fraction, b) Concrete Type

3.2 Flexure

A series of notched prism specimens were tested under third-point loading in accordance with ASTM C1609 to characterize the flexural properties of the recycled coarse aggregate concrete (RCA-C) and conventional concrete (CC) material. The notch was saw-cut into the bottom face of prism specimens at mid-span. The purpose of the notch was to predetermine the crack location and prevent multiple micro cracks from forming in the high tensile zone. A notch depth of 25 mm was adopted in this research. A displacement controlled loading rate of 0.05 mm/min was used for the prisms until the mid-span deflection reached a deflection limit of L/150. Two Linear Variable Displacement Transducers (LVDTs) were attached to a yoke to measure the mid-span deflection of the neutral axis. The flexural peak load, modulus of rapture (MOR), and toughness factor, which is the area under load-deflection curve from 0 mm to L/150, are investigated and the results are presented below.

3.2.1 Flexural Load-Deflection Response

Typical flexural load against deflection curves for CC and RCA-C mixes with V_f = 0.5, 1.0, and 1.5% are illustrated in Figure 3, with a horizontal offset to avoid overlap. Unlike CC and RCA-C mixes incorporating steel fibers, the failure in flexural prisms constructed with plain mixes was found to be sudden and brittle with relatively little cracking.

The flexural responses of the CC material with different fiber contents are compared against the RCA-C response and the results are illustrated in Figure 3. All the CC and RCA-C mixes presented a linear response until the LOP was reached. After this point the flexural strength of mixes with V_f=1% and 1.5% slightly increased until the maximum peak load was achieved. As presented in Figure 3, higher softening rate in the RCA than CC material was found. This is most probably because compared to CC material incorporating natural aggregate there is a weaker transition zone between the crushed aggregates and paste.

According to Figure 3, the RCA-C materials tend to show the similar response and peak flexural load presented by the CC material. This phenomenon is mainly attributed to the governing role of the steel fibers in both mixes.

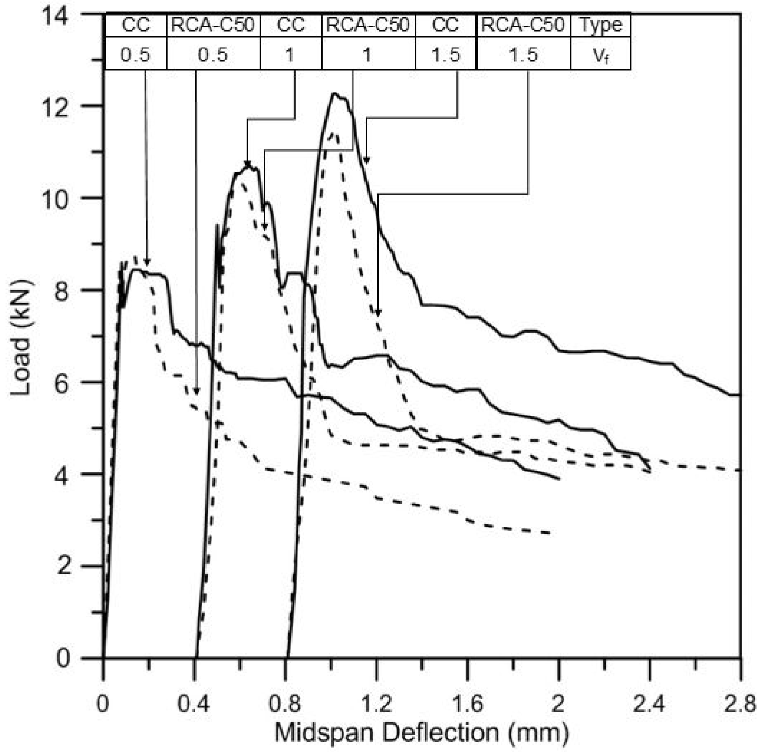

Figure 3. Flexural Strength curves base on different volume fraction

3.2.2 Influence of fiber volume-fraction on flexural strength

The calculation of modulus of rupture (MOR) was based on the proposed equation in ASTM C1609-10, where d_n represents the height of the prism after accounting for the notch, b_w is the prism width, L is the clear span, and P_{max} is the maximum flexural load.

$$MOR = \frac{P_{max}L}{b_w d_n^2}$$

The influence of fiber volume-fraction on flexural strength of conventional concrete (CC) and recycled coarse aggregate concrete (RCA-C) is summarized in Table 4. According to test results, the increase in fiber volume fraction from 0% to 0.5%, 1% and 1.5% can lead to 31, 67, 89% increase in the MOR of CC material. Similar trend was noted for RCA-C, where 63, 97, 115% increase in MOR was found as the fiber content was increase from 0 to 0.5%, 1%, and 1.5%.

Compared to CC material, the RCA-C material tends to show the similar MOR response for all the fiber volume fractions except for the V_f=0%. This indicates that the RCA-C can be a suitable alternative to conventional concrete, as it features a more economical and environmental-friendly option.

Table 4 – Flexural strength of concrete

Notation	P_{max} (kN)	MOR (MPa)	T_{150}^D (J)
CC 0	6.43	5.14	0.313
CC 0.5	8.44	6.75	11.17
CC 1	10.72	8.58	12.57
CC 1.5	12.16	9.73	14.83
RC 50-0	5.34	4.27	0.291
RC 50-0.5	8.72	6.98	8.49
RC 50-1	10.53	8.42	10.39
RC 50-1.5	11.49	9.19	10.52

3.2.3 Influence of fiber volume fraction on toughness

The improvement in the material flexural response in the post-peak phase can be captured by flexural toughness factor (FTF). The FTF is the energy equivalent to the total area under the flexural load-deflection curve up to a net deflection of L/150 (ASTM C1609).

A very poor FTF value of 0.313 MPa and 0.291 was noted for the CC and RCA-C mixes with V_f = 0% because the specimens failed in a brittle manner at cracking. In contrast, the addition of 0.5% to 1.5% volume fraction of steel fiber was observed to significantly overcome the brittleness of the matrix and improve the toughness of the CC and RCA-C mixture. According to Table 4, the increase in fiber volume fraction from 0.5% to 1% and 1.5% can lead to 12% and 33% increase in the MOR of CC material. Similar trend was noted for RCA-C, where 22% and 24% increase in MOR was found as the fiber content was increase from 0.5% to 1%, and 1.5%. According to test results, the RCA-C features a lower toughness factor, which is mainly attributed to the higher rate of softening after the peak load was achieved.

4 CONCLUSIONS

The mechanical properties in compression and flexure were experimentally investigated for conventional concrete (CC) and recycled coarse aggregate concrete (RCA-C) containing up to 1.5% volume-fraction of steel fibers. The major contributions of this research program are summarized as follows:

- The compressive strength of RCA-C with 50% aggregate replacement and 0-1.5% volume fraction of steel fiber was compared against CC material. It was found that the addition of 0.5 to 1.5% steel fibers has small effect on the peak compressive strength, regardless of the aggregate type (natural or crushed) in the concrete matrix. However, the strain corresponding to peak compressive stress increases with an increase in the fiber volume-fraction content.
- The influence of fiber volume-fraction and aggregate type on flexural strength of conventional concrete (CC) and recycled coarse aggregate concrete (RCA-C) was investigated. The increase in fiber volume fraction from 0 to 0.5, 1 and 1.5% can lead to 31, 67, 89% increase in the MOR of CC material. Similar trend was noted for RCA-C, where 63, 97, 115% increase in MOR was found as the fiber content was increase from 0 to 0.5%, 1%, and 1.5%.
- Unlike the plain CC and RCA-C material with a very poor FTF, the addition of 0.5% to 1.5% volume fraction of steel fiber was observed to significantly overcome the brittleness of the matrix and improve the toughness of the CC and RCA-C mixture.
- The promising RCA-C material response in both compression and flexure offers a suitable alternative to conventional concrete material.

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