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Compressive behavior of steel fiber reinforced recycled coarse aggregate concrete designed with equivalent cubic compressive strength

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HIGHLIGHTS

- Specimens with 0–100% RCA replacement ratio and nearly equivalent cubic compressive strength were considered.
- Combined effect of SFs and RCA on compressive behavior of SFRCAC was studied.
- An empirical formula for Young's modulus and strain as well as a constitutive model of SFRCAC were proposed.
- Crack patterns of SFRCAC were found to be different depending on fiber volume.

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ABSTRACT

This paper presents the experimental results related with the compressive behavior of steel fiber reinforced-recycled coarse aggregate concrete (SFRCAC). Compressive strength, Young's modulus and stress-strain curves were carried out on more than 100 specimens. Emphasis was placed on the combined effect of steel fibers (SFs) and recycled coarse aggregate (RCA) on the axial compressive behavior of SFRCAC with equivalent compressive strength. Test results indicate that with the addition of SFs, Young's modulus and stress-strain curves of SFRCAC are similar to those with natural coarse aggregate (NCA) concrete, but the critical strain has a significant increase with the increase of steel fiber content and RCA replacement ratio. Regression formula of compressive strength, Young's modulus, critical strain and constitutive model of SFRCAC are proposed.

1. Introduction

Recycling construction and demolition waste were initiated during the Second World War due to the difficulty of acquiring natural materials. Since then, extensive research has been conducted worldwide to develop the production of recycled materials, promoting the sustainable methods of construction. One of the most effective approaches is to use waste concrete from construction and demolition as coarse aggregate in fresh concrete. Available studies have proven that recycled coarse aggregate concrete (RCAC) is a potential solution to minimize the consumption of natural aggregate resources [1–6]. However, the study results have illustrated that recycled coarse aggregate (RCA) has higher porosity and water absorption than natural coarse aggregate (NCA), so compared to NCAC with same mixture proportion the compressive strength and Young's modulus of RCAC may decrease 20–25%, critical strain may increase 10–20% [7–11]. Although some countries have issued the relevant specifications which allow recycled aggregates to be used in structural concrete, such as Chinese standard "Technical specification for application of recycled aggregate, GJG/T204-2011" [12]. Many of these standards limit the percentage of recycled aggregate. But in some locates, RCAC has few applications in engineering due to the lack of the research on mechanical properties.

Before RCAC is used in structural members, it must be ensured that it has satisfactory mechanical properties in comparison with NCAC. Recently many studies have focused on steel-fiber reinforced recycled coarse aggregate concrete (SFRCAC). Steel fibers have been recognized as reinforcing materials that could significantly improve the mechanical performance of concrete structural components [13–16]. Previous research has shown that: (i) SFs both increase the mechanical strength and modify the fracture process and toughness of RCAC, the behavior of the SFRCAC under

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Notation of abbreviations and symbols

NCA	Natural coarse aggregate
NCAC	Natural coarse aggregate concrete
RCA	Recycled coarse aggregate
RCAC	Recycled coarse aggregate concrete
SFs	Steel fibers
SFNCAC	Steel fiber reinforced natural coarse aggregate concrete
SFRCAC	Steel fiber reinforced recycled coarse aggregate concrete
d_f	diameter of steel fibers/mm
l_f	length of steel fibers/mm
λ_f	characteristic coefficient of steel fiber
υ_f	steel fibers volume content/%
r_g	recycled coarse aggregate replacement ratio/%
f_c	prism compressive strength/ MPa
f_{cu}	cube compressive strength/ MPa
E_c	Young's modulus of concrete/ GPa
d_c	critical deformation/ mm
E_0	tangent modulus at the original point/GPa
E_p	secant modulus at the peak point/GPa
l_0	gauge length/mm
$W_{1,0}$	compression work
$R_{e,1.0}$	toughness index
ε_c	critical strain corresponding to the peak stress of SFRCAC
ε_0	critical strain corresponding to the peak stress of NCAC

compression becomes similar to that of steel fiber reinforced natural coarse aggregate concrete (SFNCAC) [17]; (ii) SFs can prevent and reduce the development of inherent micro-defects in RCAC [18]; and (iii) cost savings are significant for an optimum combination of RCAC and steel fibers due to quantified environmental benefits of recycled aggregates[19]. Therefore, SFRCAC has great potential for application in structural members if a balance between SFs content and RCA replacement ratio is achieved for the optimal mechanical performance of concrete, which would greatly improve the use of RCA in structural application. The effect of SFs on properties of RCAC, such as failure mode, compressive strength (f_c), Young's modulus (E_c), critical strain (ε_c) and stress-strain relationship may be different from NCAC. However, there is a lack of research pertaining to the coupling effect of RCA and SFs on SFRCAC under compression.

The highlight of this paper is to compare different RCA replacement ratios (r_g) and steel fiber volume contents (υ_f) in concretes with equivalent cubic compressive strength (f_{cu}). The objectives of this study are: (1) to evaluate the effect of r_g and υ_f on the f_{cu}, f_c, E_c and ε_c of RCAC; (2) to quantify the effect of r_g, υ_f and their combined effect on the stress-strain relation of RCAC; (3) to characterize the crack pattern of SFRCAC specimens under compression. In most studies to date, mixture designs differ only in the percentage of recycled aggregate. In this research, the mixture designs were altered to achieve similar compressive strength for RCAC and NCAC so as to investigate differences in other properties. This investigation will be of significance for engineering practice and provide a necessary data base for the further study of design methodology of RCAC structures. The experimental program and the result of the study are outlined in the following sections.

2. Experimental program

2.1. Materials and mixture proportion

Portland cement (P.O 42.5) was used in all mixtures. RCA was made of waste mix-ready concrete specimens obtained from a concrete testing station; the strength and age of the waste concrete were unknown. The waste concrete was crushed through a jaw crusher, and then sieved. The NCA was crushed limestone. Detailed properties of RCA and NCA are shown in Table 1. Compared to NCA, RCA had lower specific gravity, higher water absorption and higher porosity. According to the Chinese standard [20], RCA used in this paper belongs to category II, which is recommended for concrete less than 40 MPa. The particle size distribution of coarse aggregates obtained as result of the sieve analysis is presented in Fig. 1; the main difference is the percentage retained on the 9.5 mm sieve. Fine aggregate was river sand with a fineness modulus of 2.67 and apparent density of 2556 kg/m^3. The water reducing agent was polycarboxylate plasticizer, the optimum dosage was 1% of cement (by weight) and the water-reducing ratio was 25%. The plasticizer was used to ensure all the concrete mixtures had similar slump (50 mm). All aggregates were used in the air-dry condition. The SFs were hooked at both ends, and had tensile strength of 1000 MPa, mean diameter (d_f) of 0.6 mm, mean length (l_f) of 30.5 mm, and aspect ratio (l_f/d_f) of 54.6.

RCA replacement ratio (r_g) was defined as the mass ratio of RCA to overall coarse aggregate, where r_g = 0, 30%, 50%, 100% respectively. SFs volume content (υ_f) was taken as 0, 0.5%, 1%, 1.5%, 2% respectively. Eight groups of specimens in this research were designed to achieve the same target compressive strength ($f_{cu} = 45$ MPa) by slight modifications of the mixture design as previously suggested by [21]. The purpose here was to overcome the documented strength reduction of RCA by minor changes to W/C and paste volume and achieve a design strength typically specified in practice. Details of mixture proportion are listed in Table 2.

2.2. Specimen preparation

SFRCAC was mixed through a shaft mixer. First, all aggregates and SFs were put together and mixed for 2 minutes to ensure the SFs were uniformly dispersed. Then cement was added and mixed for another minute. Finally, water and water reducing agent were added together and mixed for another 2 min. No segregation or bleeding of concrete or balling of SFs was observed in any of the eight mixtures.

The slump of fresh concrete was tested right after the mixing process. For each group, three 150 mm × 150 mm × 150 mm cubic specimens were cast for test of f_{cu}, nine 150 mm × 150 mm × 300 mm prism specimens were cast for tests of f_c, E_c and stress-

Table 1
Physical Property of the RCA and NCA.

Aggregate Type	Apparent density (kg/m^3)	Bulk density (kg/m^3)	Water absorption (wt%)	Crush index (%)	Voidage (%)
RCA	2640	1412	4.85	17.7	50.3
NCA	2814	1630	1.40	8.80	44.3