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Mechanical behavior of recycled coarse aggregate concrete reinforced with steel fibers under direct shear

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ABSTRACT

Recycled coarse aggregate (RCA) concrete has attracted more and more attention worldwide in recent years due to the exhaustion of natural coarse aggregate and environmental pollution from construction and demolition waste in civil engineering. In this study, experiments were carried out on over 100 specimens to investigate the mechanical properties and failure mode of concrete with different volume content of steel fibers (0%, 0.5%, 1%, 1.5%, and 2%) and different RCA replacement ratio (0%, 30%, 50% and 100%) under direct shear load. The results show that addition of steel fibers can effectively improve the shear strength and shear toughness of RCA concrete. For a given compressive strength, the RCA replacement ratio has negligible impact on shear strength, but shear deformation and toughness increase as RCA replacement ratio reaches above a 'limiting value'. A shear strength formula for steel fiber reinforced RCA concrete (SFRCAC) based on compressive strength and characteristic coefficient of steel fiber has been put forward.

1. Introduction

Recycling construction and demolition waste is expected to contribute to solving the issue of lack of raw materials, and would allow the construction of infrastructures using a circulatory system for resources [1,2]. Recently, the demand for utilization of waste concrete become more urgent since a great amount of waste concrete produced by natural disasters, such as the Wenchuan earthquake has led to serious environmental problems in China [3,4]. Available studies have demonstrated that the recycled coarse aggregate (RCA) concrete is a potential solution to minimizing the consumption of natural resources, and utilizes the waste concrete stemming from construction demolition and natural disaster [5–7]. However, most utilization of waste concrete is limited to nonstructural applications such as aggregates in roadway sub-base due to its lower strength, reduced Young's modulus and increased deformation when incorporated into new concrete [8–11].

It has been agreed that steel fibers can improve the mechanical properties of natural coarse aggregate (NCA) concrete, such as tensile strength, toughness, fatigue life, and impact resistance [12,13]. The positive effect of steel fibers can make up for the shortcomings inherent in the use of RCA and improve the quality of RCA concrete. Adding steel fibers to RCA concrete can prevent and reduce the development of inherent micro-defects in concrete, thus making it feasible to obtain a sound material for structural applications in civil engineering [14–16]. Following this line, Carneiro et al. investigated the influence of steel fibers content (0.75%) on the stress-strain behavior of concrete made with 25% (by volume) RCA and found the addition of steel fibers and RCA could both increase the mechanical strength and modify the fracture process [17]. With the addition of steel fibers, the toughness of the RCA concrete was increased and its behavior under compression became similar to that of steel fiber reinforced NCA concrete. As well, the cost savings were significant for an optimum combination of RCA and steel fibers due to quantified environmental benefits of RCA [18]. Therefore, steel fiber reinforced RCA concrete (SFRCAC) has great potential for application in structural members if a balance between steel fiber content and RCA replacement ratio could be achieved for optimal mechanical performance. This will greatly promote the use of RCA in structural applications. However, there is very limited information concerning the coupling effect of RCA

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replacement and steel fiber content on the mechanical characteristics of concrete under direct shear [19,20].

In this study, a series of experiments was carried out to investigate the mechanical properties of SFRCAC under direct shear. The objective of this study is (1) to evaluate the shear strength of concrete with different RCA replacement ratio and steel fiber content; (2) to quantify the coupling effect of RCA replacement and steel fiber content on the deformation of concrete in direct shear; and (3) to characterize the crack pattern of SFRCAC specimens under direct shear. This paper, to the best of the authors' knowledge, is the first systematic study focusing on the coupling effect of steel fibers and RCA on the shear strength and deformation of concrete at present, which will be of significance for engineering practice and will provide a necessary data base for the design methodology of RCA concrete structures.

2. Experimental program

2.1. Materials

Portland cement (P.O 42.5) was used in all mixtures. The coarse aggregate included nature coarse aggregate (NCA) and recycled coarse aggregate (RCA). RCA was waste commercial ready-mixed concrete obtained from a concrete testing station. The waste concrete was crushed in a jaw crusher, and sieved to 20 mm maximum size. The NCA was crushed limestone with the same maximum size of 20 mm. Particle size distribution of coarse aggregates are shown in Fig. 1, all satisfied the ASTM-C33 limitation [21]. Table 1 shows the properties of RCA and NCA measured from test in this study. Compared to NCA, RCA had lower specific gravity, higher water absorption and higher porosity as expected due to the cement paste present. According to Chinese Standard [22], where RCA are classified into three categories, in which category I is the best, and can be used as NCA. RCA used in this test is belong to category II, which is in the middle level and is recommended for use in concrete compressive strength below 40 MPa. The 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 superplasticizer, with the dosage being about 1% of cement weight and the water-reducing ratio being 25%. The plasticizer was used to ensure that all the concrete mixtures had the similar slump. The coarse aggregate used was in its air-dry condition. The steel fibers used in this study were hooked at both ends with a tensile strength of 1000 MPa, a mean diameter (d_f) of 0.559 mm, a mean length (l_f) of 30.5 mm, and an aspect ratio (l_f/d_f) of 54.6.

2.2. Test parameters and mixture proportions

RCA replacement rate (r_g), defined as the percentage of RCA in overall coarse aggregate by weight, steel fiber volume content (V_f), and concrete cube compressive strength (f_{cu}) were the main parameters used in this study. According to the regulations 5.3.2 in Chinese Standard JGJ/T 240–2011 [23], for RCA belonging to category II, the standard deviation used in RCAC mixture design can take the same value of NCAC when the RCA replacement ratio is below 30%, and the RCA replacement should be blow 50%. Since the final aim is to use RCA instead of NCA in structural element, based on these considerations, this research investigates r_g as 0%, 30%, 50%, and 100%. The common volume content of steel fibers added into concrete is typically up to 2%, when viewed from the cost and workability performance; the volume ratio of steel fibers V_f in this research was taken as 0, 0.5%, 1%, 1.5%, 2%. As 30 MPa-60 MPa respectively are the common concrete grades currently used in structural elements in China, so f_{cu} was taken as 30, 45, 60 MPa.

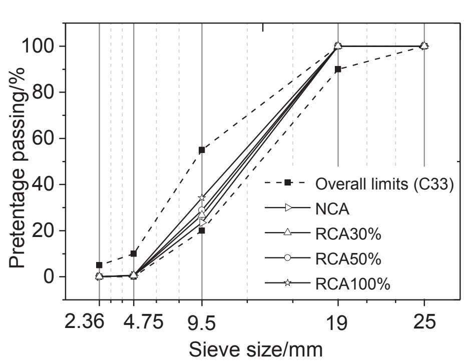

Fig. 1. Particle size distribution of coarse aggregates.

Mixture design of SFRCAC were based on target compressive strength (f_{cu} = 30 MPa, 45 MPa, 60 MPa) and target slump (50 mm), a new mixture design method was used here [24], where water-cement ratio and water content were changed to ensure that ten groups of SFRCAC achieved the target compressive strength and slump with different r_g and V_f. The concrete mixture proportions of the 10 groups are listed in Table 2.

2.3. Specimen preparation

Concrete was mixed using a shaft mixer. First, all aggregates and steel fibers were mixed for 2 min to ensure the steel fibers were well dispersed. Then cement was added and mixed for another minute. Finally, water and water reducing agent were added to the mixer, and mixed for another 2 min. No segregation or bleeding of concrete or balling of steel fibers was observed in any of ten mixtures in this study.

The slump of fresh concrete was tested right after the mixing process. For each mixture, six 150 mm × 150 mm × 150 mm cubic specimens were cast for compressive strength (f_{cu}) and splitting tensile strength (f_{ts}), six 150 mm × 150 mm × 300 mm prism specimens were cast for elastic modulus (E_c), four 100 mm × 100 mm × 300 mm prism specimens were cast for shear strength (f_{f_v}) and shear deformation. The specimens were cast in steel moulds, and compacted on a vibration table. The specimens were demoulded after 24 h and cured in a moisture room at approximately 95% relative humidity (RH) and 20 °C. The tests were performed at the age of 28 days.

2.4. Test procedures

The specimens were tested on a servo-hydraulic closed-loop testing machine with a capacity of 3000 kN. All test methods conducted the China Standard [25]. Firstly, three 150 mm × 150 mm × 150 mm cube specimens were tested at a loading rate of 0.6 MPa/s to failure to obtain the cube compressive strength (f_{cu}). Six 150 mm × 150 mm × 300 mm prism specimens were tested for elastic modulus (E_c) following Chinese Standard GB/T50081 [26], E_c is the secant modulus calculated at stress from

Table 1
Physical properties of coarse aggregate.

Aggregate type	AD (kg/m^3)	LBD (kg/m^3)	RBD (kg/m^3)	Water absorption (wt %)	Crush index/%	Porosity/%
NCA	2814	1568	1630	1.40	8.80	44.3
RCA	2640	1302	1412	4.85	17.7	50.3

AD: Apparent density; LBD: Loose bulk density; RBD: Rodded bulk density.