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Experimental study on performance of rubber particle and steel fiber composite toughening concrete

Yue Li, Yaqiang Li *

Beijing University of Technology, The Key Laboratory of Urban Security and Disaster Engineering, MOE, Beijing 100124, PR China

HIGHLIGHTS

- Effects of steel fiber and rubber particles on mechanical properties were tested.
- Effects of steel fiber and rubber particles on flexural behavior were tested.
- Effects of steel fiber and rubber particles on compression behavior were tested.
- Effects of steel fiber and rubber particles on seismic performance were tested.

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ABSTRACT

In this paper the effects of steel fiber and rubber particles on the mechanical properties, flexural behavior, compression behavior and seismic behavior of high strength concrete are studied. The results show that the compressive strength of concrete flexural strength, the elastic modulus of concrete with 5% rubber particles all decreased. After adding 0.9% steel fibers the compressive strength and elastic modulus increased slightly, but the flexural strength increased significantly. Rubber particles have an slight effect on the flexural toughness of concrete. While after adding 0.9% steel fiber the flexural toughness of concrete improve significantly, the failure mode changed from brittle fracture to ductile fracture with multiple cracking phenomenon and the descending segment of load-deflection curve becomes less steep. Rubber particles and steel fibers all can improve concrete compressive toughness obviously, increased the ductility and deformation capacity. After adding steel fibers and rubber particles, because the compressive strength of concrete reduced, the bearing capacity of seismic columns decreased slightly but the hysteresis loop changed fuller significantly, the ductility and energy dissipation capacity enhanced significantly and stiffness degradation become slower.

1. Introduction

As a low-cost building material, portland cement-based concrete was widely used in high-rise building structures, long span bridge structures, as well as some special structures due to its high compressive strength, high density, low porosity, and high durability [1–6]. However, under the external load, concrete structures usually occur to brittle failure, and with the increase of the strength grade of concrete, the brittleness increases significantly. Improving concrete toughness becomes particularly important.

With the development of automobile industry, the number of waste tires increases progressively annually. From the beginning of 1990s, the industry began to add waste tire rubber particles to cement concrete, to improve the toughness and impact resistance and have the advantages of light weight, sound insulation, energy absorption, energy consumption [7–9]. In the present, scholars have carried out a lot of research, which mainly concentrated in the effects of rubber content, surface conditions on workability and mechanical properties of concrete [10–13]. For instance, Rivas-Vázquez [14] disposed rubber particles surface with different solvent to improve the adhesion of rubber with concrete matrix, and observed using acetone treatment caused by the change of mechanical properties of samples. Eshmaiel [15] replaced the aggregate and cement with waste rubber strips and rubber powder, and the results show that the reduction of compressive strength depends on rubber size and amount of substitution. Eldin and Khatib [16–17] studied the effects of using rubber block to replace coarse aggregate, and the results show that the compressive strength and splitting tensile strength both decreased, but the toughness and energy absorption enhanced obviously. Through hammer drop test, Ilker [18] found that rubber particles

* Corresponding author.
E-mail address: yaqiangli@163.com (Y. Li).

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can improve the impact resistance of concrete, especially the larger rubber particles, which can greatly improve the impact resistance performance.

As a new type of reinforced concrete, steel fiber has excellent mechanical properties. The steel fiber can prevent the formation and development of cracks in the concrete, enhance the toughness of the concrete, and improve the deformation and energy dissipation capacity of concrete structures. At present, the domestic and foreign scholars have carried out a lot of experimental research on steel fiber reinforced concrete [19–22]. Studies have mostly focused on the performance of the workability, mechanical properties (compressive strength, tensile strength, etc.), flexural toughness, impact resistance and dynamic characteristics. For example, Lok [23] had studied the dynamic characteristics of steel fiber reinforced concrete and found that compared with static value, dynamic uniaxial compressive strength of steel fiber reinforced concrete increases moderately under a relatively high strain rate, and the tensile splitting strength increases many times with moderate strain rate loading compared with its static value. Banthia [24] had studied the impact resistance of fiber reinforced concrete and found that macro-steel fibers can improve more effectively the toughness than micro-fibers. Gonzalo [25] had studied the flexural behavior of steel fiber reinforced concrete under impact loading and found that dynamic increase factors of peak bending strength of SFRC with smooth and prismatic fibers are higher than tensile strength of plain concrete and increase with the fiber content. Kim [26] had studied the durability of steel fiber reinforcement concrete and found that compared with PP and PVA fibers steel fibers showed the highest strength to conditioning.

The rubber concrete and steel fiber reinforced concrete has been studied a lot, but for the effects of rubber particles and steel fibers on the flexural behavior, compressive behavior and seismic performance, especially the rubber particles and steel fibers composite toughening effect, there are still less, at present. In addition, in the past scholars usually use reasonable reinforcement method to meet the seismic requirements of frame columns, ignoring the energy dissipation capacity of concrete itself. This paper studies the effects of rubber particles and steel fiber on the flexural behavior, compressive behavior and the composite toughening effect of rubber particles and steel fibers. The seismic performance of composite toughened concrete columns is also studied systematically.

2. Experiment profiles

2.1. Raw materials

The cement used in the study was 42.5portland cement, and the chemical and physical properties of cement [27] was shown in Table 1. First grade fly ash with density of 3.11 g/cm3 was used, and the chemical and physical properties of fly ash [28] was shown in Table 2. The continuous grading crushed stone was used with the particle size of 5 $\sim$ 25 mm. The fine aggregate was well gradation medium-sized sand with the fineness modulus 2.64. The superplasticizer was polycarboxylate superplasticizer with the water-reducing ratio 25% and 35% solid content. The hooked-end steel fiber was used. The properties of steel fiber are shown in Table 3. The steel fibers shape and dimensions were shown in Fig. 1. The particle size of rubber particles is 2–4 mm, shown in Fig. 2. The longitudinal reinforcement and stirrup in seismic columns are HRB500 and HRB400 grade steel respectively, and the mechanical properties of steel bar were shown in Table 4.

2.2. Mix design

The mix design of concrete is shown in Table 5. In addition, the rubber particles content was determined by partial replacement of fine aggregate (sand) by volume. The steel fibers content was determined by partial replacement of concrete by volume.

2.3. Testing methods

The compressive strength, flexural tensile strength and elastic modulus were tested by triplicate 100 mm cube samples after curing 28 days at a loading rate of 0.5 MPa/s according to GB/T 50081-2002 standard test method for the mechanical properties of ordinary concrete [29]. The average values of three samples were used as the strength values in each same experiment.

Flexural behavior of concrete was tested by four point flexural beam test using 100 * 100 * 400 mm sample at a loading rate of 0.5 mm/min. The average values of three samples were used as the final result in each same experiment. Test schematic diagram was shown in Fig. 3.

The compression behavior was tested by axial compression using 100 * 100 * 400 mm sample at a loading rate of 0. 5 mm/min. The average values of three samples were used as the final result in each same experiment. Test schematic diagram was shown in Fig. 4.

Seismic performance: No. A and D were tested to study the effect of steel fiber and rubber particles composite toughening on the seismic performance of concrete, the reinforcement drawing of seismic column was shown in Fig. 5. Seismic performance was tested by low cyclic loading with an axial compression ratio of 0.27. One sample was tested in each same experiment. Axial loads and horizontal loads are loaded by vertical jack and horizontal hydraulic servo actuator, respectively. The loading scheme is controlled by displacement, each stage displacement cyclic loading two times, until the sample destroyed, and the loading system schematic diagram was shown in Fig. 6. All the experimental data are recorded by data collection instrument automatically.

3. Results and analysis

3.1. Mechanical properties

The mechanical properties of all samples are shown in Table 6.

As can be seen from Table 6, the compressive strength and elastic modulus of concrete with 5% rubber particles decreased obviously, and the flexural strength decreased slightly. Compared to sample A, the compressive strength of the sample B decreased by 30%, the modulus of elasticity decreased by 32.8%, and the flexural strength decreased by 9.5%. This is mainly because rubber particles as toughening phase are distributed in concrete which form many soft weakness points, thereby reducing the strength of concrete. Besides, weak interfacial transition zones are formed between

Table 1
Chemical and physical properties of portland cement.

MgO (%)	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SO_3 (%)	Loss (%)	Specific surface area (m^2/kg)	Density (g/cm^3)	Compressive strength (MPa)		Flexural strength (MPa)	
									3 days	28 days	3 days	28 days
4.94	60.62	21	4.62	2.86	4.23	1.73	806	3.46	27.4	48.5	4.7	7.3