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Using Crumb Rubber to Improve the Properties of Concrete from the Sustainability Point of View

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Abstract: In the past decade, the economy of China has been increasing at a remarkable speed, which causes the rapid increase of automobile industry. Researches in past years demonstrated that the incorporation of crumb rubber into concrete reduces the mechanical strength of concrete. However, properties such as plastic shrinkage cracking resistance, dry shrinkage cracking resistance, frost resistance, impact resistance, fatigue resistance etc. are improved due to the deformable feature of crumb rubber. Therefore, it is expected that using crumb rubber in concrete not only improves the properties of the material, but also reduces the environmental pressure of handling waste tires.

Key words: Crumb rubber, concrete, property, sustainability.

1. Introduction

In China, the automobile production is increasing rapidly with the fast development of economy. Thus the number of discarded tires is also increasing quickly with the huge car ownership in China. It is estimated that the total weight of discarded tires reached 2.53 million in 2011 [1]. Currently, the recycling network is not mature yet, which leads to the difficulty in disposal of the discard tires in China.

As is well known, ordinary cement concrete is a quasi-brittle material, which cannot satisfy such requirements as low unit weight, high toughness, and impact resistance etc. for some special applications. One way to improve the toughness of concrete is to incorporate crumb rubber particles to replace a part of the aggregate in concrete. The inclusion of crumb rubber into concrete results in higher resilience, durability, and deformation ability [2]. Epps [3] used recycled tire rubber in highway asphalt mix. Eldin and Senouci [4] investigated the strength and toughness of concrete with a portion of aggregates replaced by waste tire chips. Top ɋu [5] studied the effect of particle size and content of tire rubbers on the mechanical properties of concrete. The results revealed that the compressive strength and split tensile strength were reduced, while the toughness and ability of fracture energy absorption were enhanced significantly [6, 7].

The objective of this paper is to reveal the comprehensive properties of crumb rubber included concrete. The performance investigated covers deformation, plastic shrinkage, impact resistance and fatigue performance. It is expected that the understanding of the influence of crumb rubber on the properties of concrete can help promote the application and consumption of crumb rubber in concrete, and therefore contribute to the sustainable development of concrete in the future.

2. Materials and Mix Proportions

2.1 Materials

P·II 42.5R Portland cement, river sand with fineness modulus of 2.6 and bulk density of 2,610 kg/m^3, and crushed limestone and basalt of 5-20 mm continuous grading with bulk density of 2,840 kg/m^3 and 2,790 kg/m^3, respectively, were used to prepare concrete. The mechanically crushed rubber particles from waste tire

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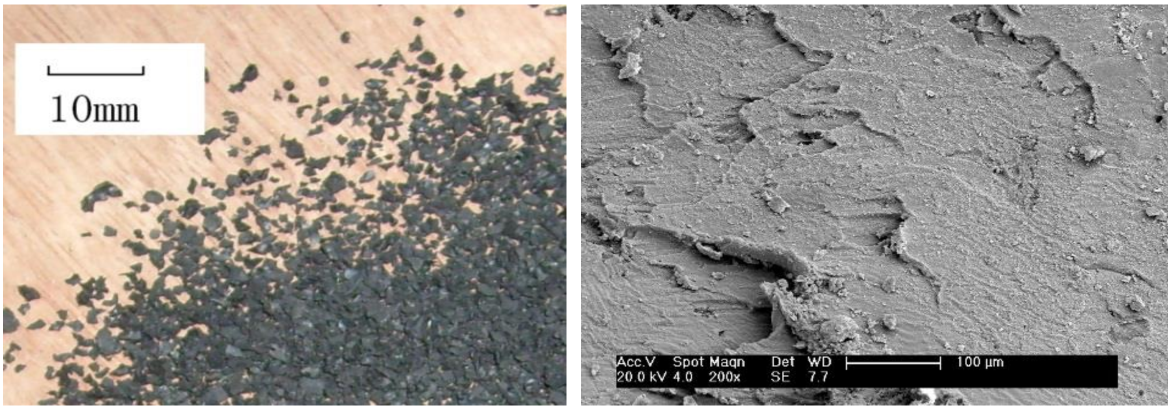


Fig. 1 The size (up) and surface (under) of rubber particles.

Table 1 Mix proportion of concrete (kg/m^3).

	Cement	Water	Fine aggregate	Coarse aggregate[a]	Rubber	Fiber[b]	Superplasticizer
NC	457	165	575	1248	0	0	4.57
RC 25	457	165	431	1248	60	0	4.57
RFC 25	457	165	431	1248	60	1	4.57

[a] Limestone was used in fatigue test and basalt was used in deformation and impact test.

[b] PP fiber was used in fatigue test and PVA fiber was used in deformation and impact test.

were 2-3 mm in diameter, owning rough surface, as can be seen from the right figure in Fig. 1, which contributes to the good bonding between cement paste and rubber particles. The density of waste rubber is 1.1 g/cm^3. PP (Polypropylene) fiber and PVA (polyvinyl alcohol) fiber were used. The length of PP fiber is 15 mm and the diameter is 18-30 μm. For PVA fiber, the length is 12 mm and the diameter is 39 μm. The tensile strength and elastic modulus of PP fiber is 300-450 MPa and 3-3.5 GPa, respectively, that of PVA fiber is 1,600 MPa and 35-40 GPa. A polycarboxylate-type superplasticizer JM PCA-I from the Subote company was used to adjust the slump of all the fresh mixtures at the level of around 160-200 mm. For deformation, impact and fatigue tests, three types of concrete mixtures were considered: (1) plain concrete (NC), (2) crumb rubber included concrete (RC), and (3) fiber reinforced crumb rubber included concrete (RFC). For crumb rubber included concrete, 141 kg of sand in the mixture of plain concrete was replaced with 60 kg of crumb rubber. The mix proportions of three types of concretes are shown in Table 1.

3. Specimen Preparation and Test Methods

3.1 Flexural and Fatigue Tests

All the specimens for flexural and fatigue test were cast in 100 × 100 × 400 mm steel molds and the specimens were cured in a room at 22 ± 3 °C and 95% ± 2% relative humidity. The cure time was 1 year for fatigue test and 6 months for flexural test. An MTS 810 testing machine was used for fatigue and flexural test. For the fatigue test, a constant-amplitude sine wave loading mode and acoustic emission method were used. The peak loads for fatigue cyclic loading were 80%, 70%, and 60% of the ultimate load of each type of concrete, corresponding to stress levels (S) of 0.8, 0.7 and 0.6, respectively. The R-ratio (the ratio of valley load to peak load) is 0.1. The load frequency was 10 Hz. The peak load and the valley load of each concrete are given in Table 2 [8].

3.2 Plastic Shrinkage Cracking Test

The plastic shrinkage cracking test (Fig. 2) was carried out according to CCES 01-2004. After casting, the samples (600 × 600 × 63 mm) were covered by plastic film [9]. Two hours (2 h) later, the samples were uncovered and

Table 2 Flexural strength of concretes and peak and valley load for fatigue test.

	Ultimate load (kN)	Average flexural strength (MPa)	Peak load/valley load (kN)		
			S = 0.6	S = 0.7	S = 0.8
NC	19.9	5.96	11.9/1.19	13.9/1.39	15.9/1.59
RC 25	17.4	5.22	10.4/1.04	12.2/1.22	13.9/1.39
RFC 25	18.51	5.55	11.1/1.11	13.0/1.30	14.8/1.48

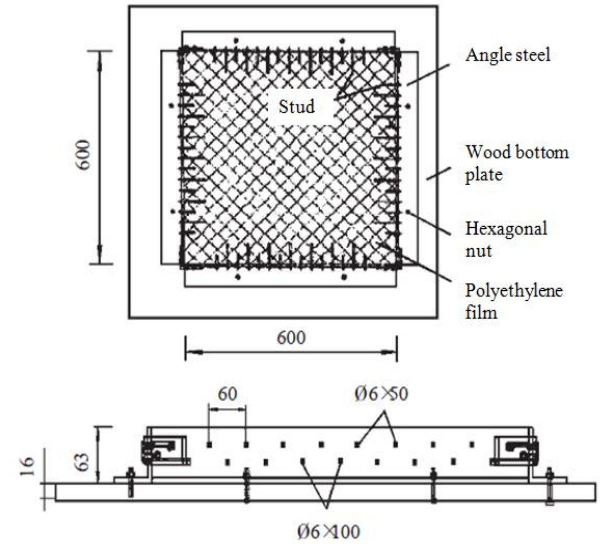


Fig. 2 Set-up of plastic shrinkage test [9].

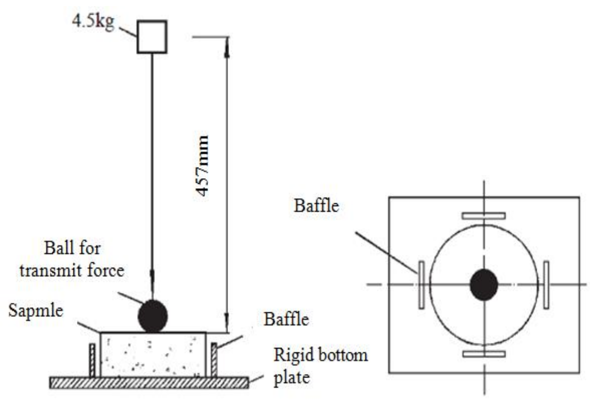


Fig. 3 Set-up of impact test [9].

blown by fans with 8 m/s wind speed for 22 h. The time when the first crack appeared, number of cracks and the total cracks area were investigated to assess the plastic shrinkage cracking resistance of the specimens.

3.3 Impact Test

The impact test (Fig. 3) was carried out according to ACI-544 [9]. The weight of drop hammer is 4.5 kg, the falling height is 457 mm. The thickness and diameter of specimen are 60 mm and 150 mm, respectively. The impact numbers at first crack and at failure are recorded respectively. The total impact energy is calculated by following equation:

$$W=N_c \times mgh$$

where:

Nc: the number of impact

m: the weight of drop hammer (4.5 kg)

h: the falling height (457 mm)

g: the gravity acceleration (9.81 m/s^2).

4. Results

4.1 Deformation

Stress-strain curves of concrete under uniaxial compression are shown in Fig. 4. The compressive strength of both crumb rubber included concrete and fiber reinforced crumb rubber included concrete is lower than plain concrete, but the peak strain is higher. Compared with NC, the uniaxial compressive strength of RC 25 and RFC 25 decreased 34% and 42%, respectively. The peak strain of RC 25 and RFC 25 is 1.74 times and 1.92 times that of NC, respectively. From the photos of these specimens at failure, we can find that the incorporation of crumb rubber in concrete changed the brittle failure of ordinary concrete, the concrete with crumb rubber became more ductile and the specimen still kept its integrity after failure.

4.2 Plastic Shrinkage Cracking

The test results of plastic shrinkage cracking were shown in Table 3. The crumb rubber included concrete showed excellent plastic shrinkage resistance and no cracks were observed during the test. The plain concrete, however, generated 8 cracks, among which, the width of 3 cracks ranged between 1-2 mm, 2 cracks between 0.5-1 mm and 3cracks less than 0.5 mm.

Table 3 Test results of plastic shrinkage cracking.

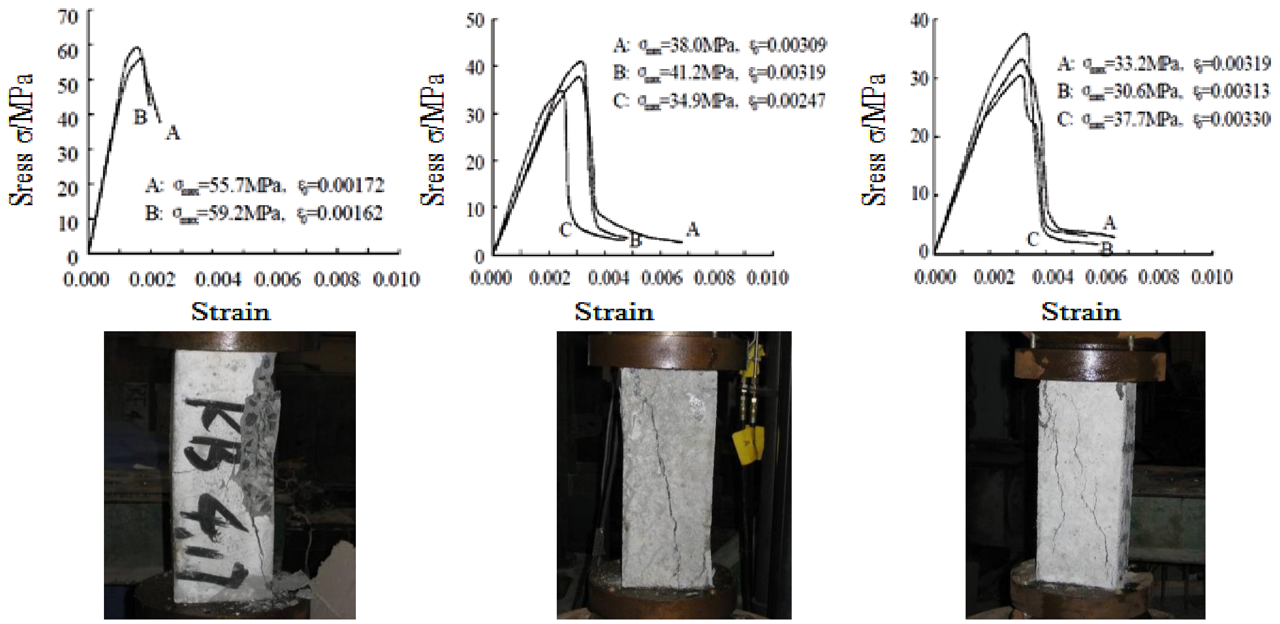
Sample	Time of initial crack appeared (h)	*N*	*a* (mm^2)
NC	3	8	106.3
RC 25	No cracks in 24 h	0	0

N: number of cracks, *a*: total area of crack.

4.3 Impact Resistance

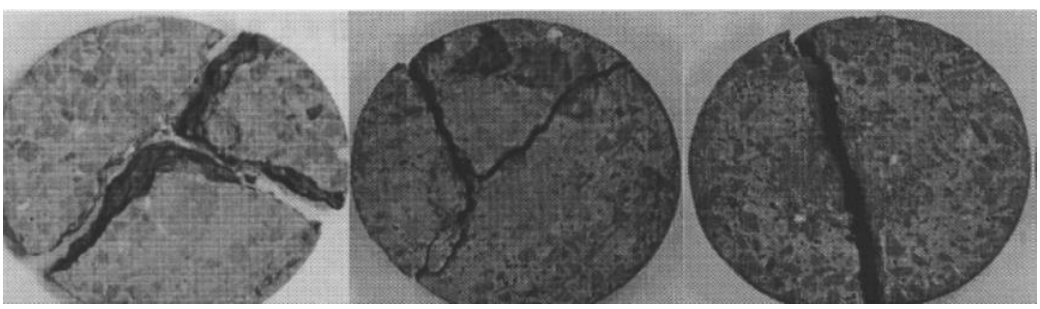
Fig. 5 shows the specimen before and after impact test. For the plain concrete, a shallow pit with 3-4 mm depth appeared at the position of the impact at failure. For crumb rubber and fiber reinforced crumb rubber concrete, the depths of shallow pits at failure were 10 mm and 15 mm, respectively.

In Table 4, the number of impacts of crumb rubber included concrete was much higher than plain concrete. The impact number of RC 25 and RFC 25 at first crack was 6.2 times and 8.3 times that of NC, respectively. After the first crack, FRC 25 can bear 18 more impacts, but NC can bear only 3 more impacts before failure. It shows that crumb rubber included concrete owns higher ductility. Due to the deformation of rubber particles, the crumb rubber included concrete can absorb more impact energy. During the propagation of micro cracks, the rubber particles on the propagation path of cracks may decrease the stress concentration at crack tip by deformation and therefore inhibit the extension of cracks. In RFC 25, the propagation of cracks was further inhibited by the PVA fiber which had high elastic modulus and high ultimate elongation [10].



(a) NC after 194 impacts (b) RC 25 after 916 impacts (c) RFC 25 after 1,306 impacts

Fig. 4 Failure of concretes after impact test.



(a) NC after 194 impacts (b) RC 25 after 916 impacts (c) RFC 25 after 1,306 impacts

Fig. 5 Failure of concretes after impact test.

Table 4 Impact test result.

Sample	N_1[a]	N_2[b]	ΔN	W/J
NC	132 (77/128/190)	135 (79/132/194)	3	2,724
RC 25	826 (744/831/902)	837 (751/843/916)	11	16,886
RFC 25	1,096 (918/1,090/1281)	1,114 (932/1,103/1,306)	18	22,474

[a] N_1 means number of impacts when the first crack appeared, it is the mean value of three specimens in parenthesis.

[b] N_2 means number of impacts when the specimens were broken.

Table 5 Average fatigue life of three types of concrete.

	Stress level (s)		
	0.6	0.7	0.8
NC	110,878	21,747	1,725
RC 25	1,118,634	321,746	12,634
RFC 25	1,457,667	337,766	20,235

4.4 Fatigue Performance

Table 5 shows the fatigue life of each specimen at specified stress level. For each type of concrete, five specimens were tested at each stress level. It can be seen that among the three types of concretes, the fatigue life of RFC is the highest, and that of NC is the lowest. For instance, the average fatigue life of NC, RC, and RFC at a stress level of 0.7 is 21,747, 321,746 and 337,766, respectively. At a stress level of 0.8, the values are 1,725, 12,634, and 20,235, respectively. The fatigue life of RC 25 and RFC 25 is one magnitude higher than that of NC. This result demonstrates that the inclusion of 60 kg rubber particles in 1 m^3 concrete can greatly increase the fatigue life of cement concrete, and the addition of PP fiber in crumb rubber included concrete can further enhance the fatigue life.

5. Discussion and Contribution of the Utilization of Crumb Rubber to the Sustainable Development of Concrete

From the above experimental results, it can be concluded that the inclusion of rubber particles in concrete can greatly improve the deformation capacity, plastic shrinkage cracking, impact resistance and fatigue performance of plain concrete. The analysis of AE signals shows that the damage process of rubberized concrete is quite different from that of plain concrete [8]. For rubberized concrete, not only are the AE events/hits less but the energy of these signals are also lower as compared with plain concrete. It can be therefore summarized that the incorporation of crumb rubber in concrete can improve the ductility of concrete and hence properties relating to the ductility of concrete can be enhanced although the mechanical strength and the elastic modulus may be reduced. However, the reduction in mechanical strength can be compensated via using lower water cement ratio to produce concrete.

In China, the consumption of commercial concrete was about 1.42 billion m^3 and over 5.2 million tons of rubber was generated from waste tires in 2011. It is therefore no problem to accommodate the crumb rubber in concrete only if the contractors can understand the superior properties of crumb rubber included concrete and the cost of crumb rubber is proper. One of the current obstacles for the utilization of crumb rubber in concrete in China is the relative high cost of crumb rubber.

6. Conclusions

From the technical point of view, the inclusion of rubber particles in concrete can greatly improve the performance of plain concrete, although the mechanical properties may decrease.

From the sustainable point of view, the utilization of crumb rubber in concrete can solve the potential problem caused by improper disposal of waste rubber and the use of raw mineral materials, especially fine aggregate, can be reduced.

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