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Dynamic behavior of crumb rubber concrete subjected to repeated impacts

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ABSTRACT

An experimental investigation on the dynamic mechanical behavior of the crumb rubber concrete (CRC) with crumb rubber contents varying from 0%~20% (equal volume of fine aggregate replacement) subjected to repeated impacts was conducted using Split-Hopkinson Pressure Bar (SHPB). The influences of rubber contents on dynamic properties of CRC subjected to repeated impacts were explored. The test results show that the impact resistance times of CRC increases at the beginning and then decreases with the increase of rubber contents, whereas the static compressive strength of CRC decreases with the increase of rubber contents. The capability of energy absorption of CRC under impact loading is higher than that of normal concrete (NC). The incorporation of rubber enhanced the toughness of CRC significantly and the impact resistance of CRC is greatly increased.

1. INTRODUCTION

A large number of automobile, truck and off-road tires are discarded all over the world every year, however, only a small proportion is recycled. Low-degrade rubber and scrap wire are normally land-filled. Landfill of used rubber tires is a major environmental problem around the world. Rubber tires not only consume significant landfill space, but the risk of fire poses a serious threat to the environment. Meanwhile, waste tire rubber constitutes a serious worldwide problem due to the lack of landfills and the health hazards associated with these landfills. In addition to the environmental motivation for providing a means of recycling large quantities of waste tire rubbers, the use of tire rubber particles provides a new type of concrete that has unique mechanical and fracture criteria. One field of application where low-degrade rubber or scrap wire can be used is the manufacture of concrete. Since the early 20th century, professor Shuaid Ahmad of North Carolina State University obtained rubber powder by crushing scrap tires, then the rubber powder was mixed with normal concrete (NC) to made

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rubberized concrete (RC). Many researchers (Khatib et al 1999, Raghvan et al 1998, Sukontasukkul et al 2006, Nabil et al 2004, Skripkiunas et al 2007, Olivares et al 2004) have studied the properties of RC. The aim of the present work was the dynamic characteristics of RC materials. Studies achieved so far shows that compared with NC, the impact resistance of RC material is much more prominent, so it is recommended by Olivares et al (2002), Suaris and Shah (1983), Reda Taha et al (2008), Ling et al (2009), Zheng et al (2008) and Liu et al. (2012) for airport runway, highway pavement, bridge decks as well as structures in which the performance of anti-impact, anti-explosion and anti-seismic property are needed. Research results showed that the increase of the percentage of shredded waste tire chips has significant effects on the reduction of vehicle peak deceleration forces and thus the impact severity. Moreover, it revealed that specimens with 20% to 40% aggregate replacement gives better impact performances and meantime has not significant reduction to concrete strength. The study of dynamic mechanical behavior of concrete materials subjected to repeated impacts has a very important engineering significance, as it is a normal condition that concrete materials are often subjected to impact loads in practical engineering.

SHPB device can be used conveniently to record the dynamic strain-time curves and stress-time curves of materials under impact loads, therefore SHPB test technology is widely used in research field of the dynamic characteristics of strain rate sensitive materials such as concrete. Zhao et al. (2008) tested rubber particles modified mortar subjected to repeated impacts by using hammer-drop tests based on code ACI-544. Test results of Zhao et al (2008) showed that the impact property of concrete is improved obviously due to the addition of rubber particles. Concrete with 25% rubber included (equal volume of sand replacement) can resist 6.2 times higher impact attack than concrete without rubber although its compressive strength is 34% lower than that of normal concrete. However, as the hammer-drop tests neither consider the inertia effect, nor obtain stress-strain curves, the measured data can only be used to compare on a relative sense. In this paper the experimental study is designed to investigate the influence of rubber contents on the dynamic properties of CRC subjected to repeated impacts by SHPB.

2. EXPERIMENT

2.1 Material used

In preparation of the specimens for the experiments, the following materials were used: ordinary Portland cement with 42.5 MPa 28-day compressive strength, river sand with a fineness modulus of 2.6 (2.540 specific gravity), crushed stone aggregates with maximum size of 15.0 mm (2.685 specific gravity), water-reducing admixture (water reducing rate is 30%) and water for mixing and curing.

The crumb rubber was obtained by mechanical grinding from outer surface of scrap tires. The average rubber grain size is 2 mm (1.060 specific gravity). In this paper, normal strength concrete as control concrete without rubber and four series of CRC with 2 mm size and different rubber contents were used. The mix proportions of the concrete series were done using the absolute volume method. Rubber contents of 5%, 10%, 15%, and 20% replacing same volume of fine aggregates (sand) in the control concrete were used respectively. The tested concretes were denoted as NC, CRC-5, CRC-10, CRC-15 and CRC-20 respectively. The detailed concrete mixing proportions are given in Table 1.

Table 1 Mixing proportions of NC and CRC (kg/m^3)

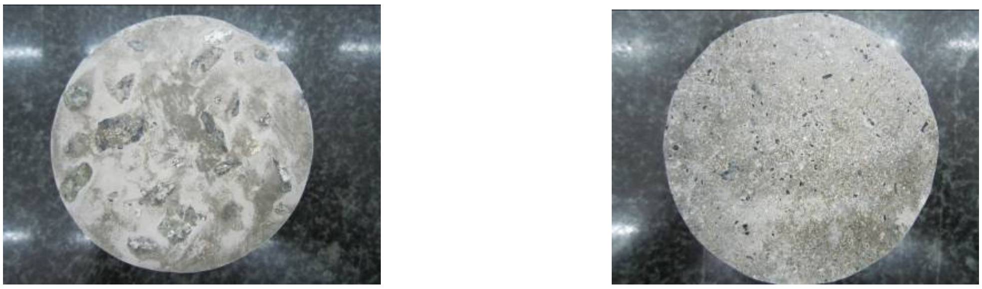
Type	Water	Cement	Sand	Crushed stone	Crumb rubber	Water reducing admixture
NC	148	420	558	1301	0	6.3
CRC-5	148	420	530	1301	11.64	6.3
CRC-10	148	420	502	1301	23.29	6.3
CRC-15	148	420	474	1301	34.93	6.3
CRC-20	148	420	446	1301	46.57	6.3

2.1 Preparation of specimens

In the SHPB tests, the concrete materials' own factors of small deformation, brittleness and poor uniformity were considered. The aspect ratio of 1 for cylindrical specimens was taken based on research of Grote et al (2001) to ensure that the stress wave propagation uniformly within the specimens and the inertia effects and the friction effects were considered. The size of the cylindrical specimens is shown in Fig. 1. There are five different types, each type has 5 specimens with 70 mm diameter and 35±0.05 mm length respectively. In addition, each type has 3 corresponding specimens of 150 mm cube sizes for 28-day quasi-static compressive tests.

(1) Diameter (2) Length

Fig. 1 Size of the cylindrical specimens



(1) NC (2) CRC

Fig. 2 Cross section of cylindrical specimens

It is worth mentioning that the surface of cylindrical specimens must be treated by grinding machine so that the surface's degree of non-parallel is within 0.05 mm and the specimens must be lubricated by Vaseline before SHPB tests. The size and cross sections of cylindrical specimens are shown in Fig.1 and Fig. 2.

2.3 Experimental principle of SHPB

The SHPB test set-up is shown in Fig. 3. The set-up consists of a striker bar which is propelled by a gas gun, an input bar, an output bar, a stopper (damper), a velocity measurement system and a data acquisition system. The cross-sectional diameters of the input bar at two ends are different, the smaller one on the left side is 37 mm, which is coincident with that of the striker bar. The larger one on the right side is 74 mm, which is equal to the output bar. The lengths of striker, input bar and output bar are 800 mm, 3000 mm (L1) and 1500mm (L2) respectively in this study. The tested specimen was sandwiched between the input and output bars.

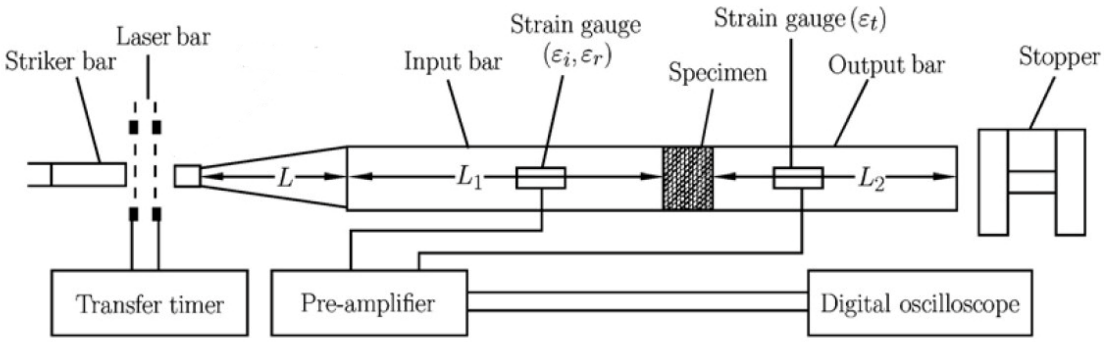


Fig. 3 SHPB test set-up

The SHPB technique is based on the theory of one-dimensional wave propagation in an elastic bar. According to the theory of one-dimensional wave propagation (Lifshitz, 1994), if a long bar is ideal elastic material, the disturbance (except for high-frequency wave) of the bar end will travels along the bar without deformation with elastic wave velocity. The loading compressive stress wave is initiated by the impact of the striker bar on the input bar, the incident stress wave signal is recorded by strain gauge on input bar as $\varepsilon_I(t)$. The stress wave is partially reflected on the interface and partially transmitted to the specimen when it reaches the interface between the input bar and the specimen. The reflected stress wave signal can also be recorded by strain gauge on input bar as $\varepsilon_R(t)$. At the interface between the specimen and the output bar, the stress wave is again partially reflected and partially transmitted, the transmitted stress wave signal is recorded by strain gauge on output bar as $\varepsilon_T(t)$. The transmitted stress wave finally was absorbed by the stopper.

The SHPB technique is based on the one-dimensional elasticity wave propagation theory, then, the following assumptions are made based on Kolsky's (1949) investigation:

1) The wave propagation in the bars is well approximated by one-dimensional elasticity wave propagation theory that does not consider the off-axial stress.
2) The stress and strain in the specimens are uniform in the axial direction that the radial-inertia and friction effects of the specimens are negligible.

According to the one-dimensional elasticity wave propagation theory, stress-strain relationship of the specimens can be draw from those wave signals of $\varepsilon_I(t)$, $\varepsilon_R(t)$ and $\varepsilon_T(t)$. The basic equations of the dynamic stress $\sigma(t)$, the dynamic strain $\varepsilon(t)$ and the strain rate $\dot{\varepsilon}(t)$ are shown as Eq. (1), Eq. (2) and Eq. (3) based on Meyers's (2002) study:

$$\sigma(t) = E_0 \frac{A_s}{A_0} \varepsilon_T(t) \tag{1}$$

$$\varepsilon(t) = -\frac{2c_0}{l_s} \int_0^t \varepsilon_R(t) dt \tag{2}$$

$$\dot{\varepsilon}(t) = -\frac{2c_0}{l_s} \varepsilon_R(t) \tag{3}$$

where A_0, E_0 and C_0 are the cross-sectional area, Young's modulus and elastic wave velocity of the bars respectively. A_s and l_s are the cross-sectional area and original length of the specimen respectively.

In the SHPB tests, CRC with crumb rubber contents varying from 0%~20% are subjected to repeated impact under the same way (the pressure of the gas gun fixed at 0.20 MPa), its strain rate ranges from 18.3 s-1 to 30.6s-1. The stress wave of repeated impact used in the SHPB tests without specimen is shown in Fig. 4.

3. TEST RESULTS AND DISCUSSIONS

The quasi-static compressive tests were designed according to the Chinese Code for test method standard of mechanical properties of normal concrete (GB/T50081-2002, 2002). The cubic compressive strength of 28-day of NC, CRC-5, CRC-10, CRC-15 and CRC-20 was determined as 49.7 MPa, 45.7 MPa, 40.9 MPa, 33.0 MPa and 28.1 MPa respectively. In the SHPB tests, specimen were sandwiched between the input and output bars by friction. Due to the interface between specimen and bar cannot subject to reflected tensile wave which appears while the input bar unloading, the specimen will drop off to the short tube which is designed for connecting the input and output bars (specimen is enclosed in the tube for safety consideration). Therefore, the specimen has not been influenced by the tensile wave during testing. It can be immediately re-installed for the next impact until it can not maintain its integrity, then the test is ended. Stress-strain curves of NC, CRC-5, CRC -10, CRC -15 and CRC -20 under different impact times are shown in Fig. 5 to Fig. 9 respectively. The number (1)-

(4) in Fig. 5 to Fig. 9 represents the order of repeated impacts. Topcu's (1997) research about toughness of concrete material indicates that energy capacities consumed during loading can be valued by measuring the areas under the stress-strain curves. NC and CRC series' strain rate, peak stress, ultimate strain and area under the stress-strain curves at each impact were obtained, and were shown in Table 2.

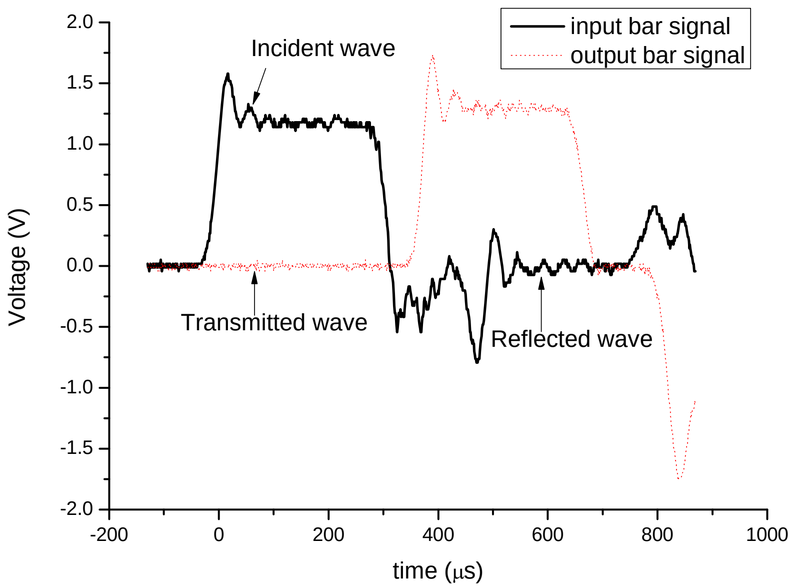


Fig. 4 Stress wave of repeated impacts

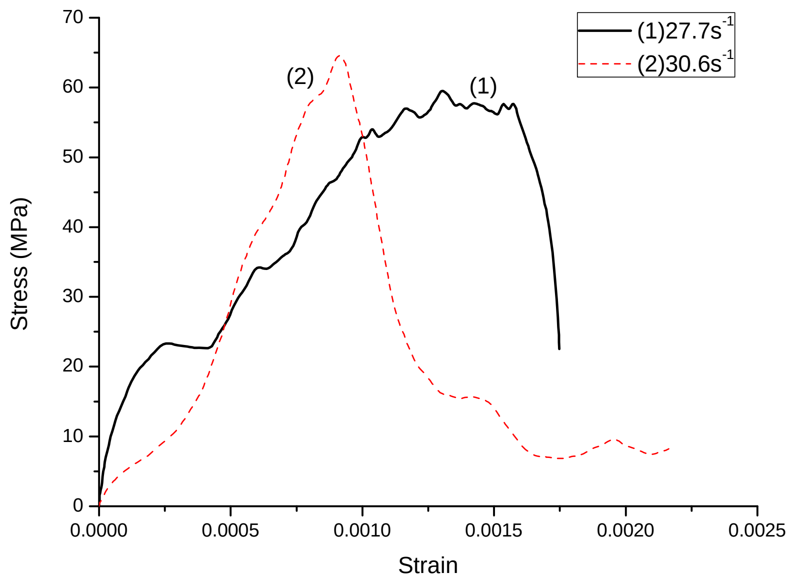


Fig. 5 Stress-strain curves of NC under different impact times

Table 2 Summary of SHPB tests results

Type	Order of the impact	Strain rate (s^{-1})	Peak stress (MPa)	Ultimate strain (‰)	Area under the stress-strain curve	Sum of the area
NC	1	27.7	59.5	1.748	0.0480	0.1182
	2	30.6	64.6	2.164	0.0702	
CRC-5	1	24.9	51.5	2.286	0.0504	0.1625
	2	25.1	53.5	2.370	0.0490	
	3	24.3	55.9	2.646	0.0631	
CRC-10	1	22.6	45.7	3.211	0.0889	0.2782
	2	20.4	48.6	2.999	0.0623	
	3	18.3	51.3	2.599	0.0605	
	4	19.4	50.6	2.880	0.0665	
CRC-15	1	24.2	35.5	3.571	0.0750	0.2338
	2	21.2	41.8	3.226	0.0520	
	3	21.4	40.5	3.126	0.0532	
	4	21.7	41.1	3.264	0.0536	
CRC-20	1	19.0	34.9	3.912	0.0641	0.1973
	2	21.2	36.0	4.970	0.0675	
	3	23.3	32.1	5.255	0.0657	

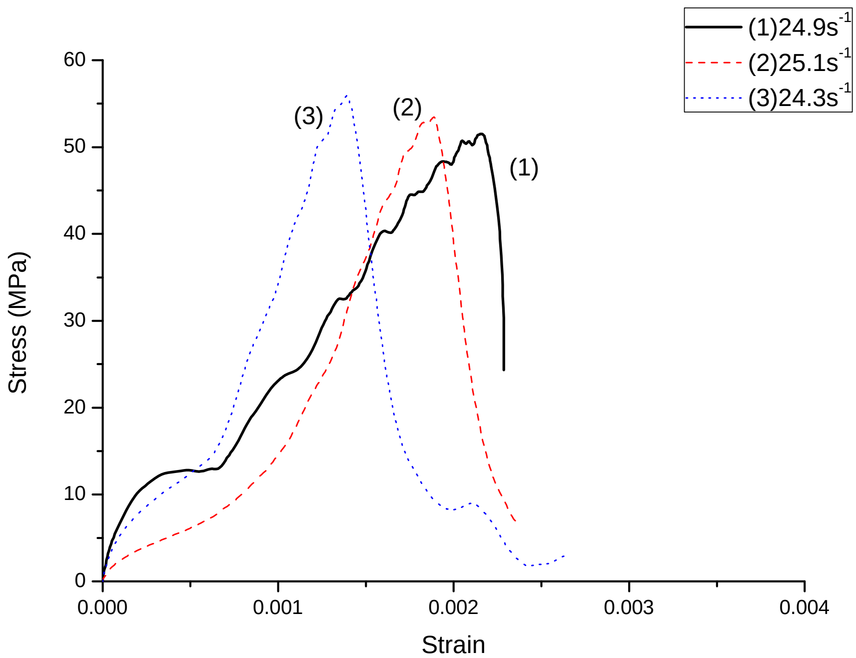


Fig. 6 Stress-strain curves of CRC-5 under different impact times

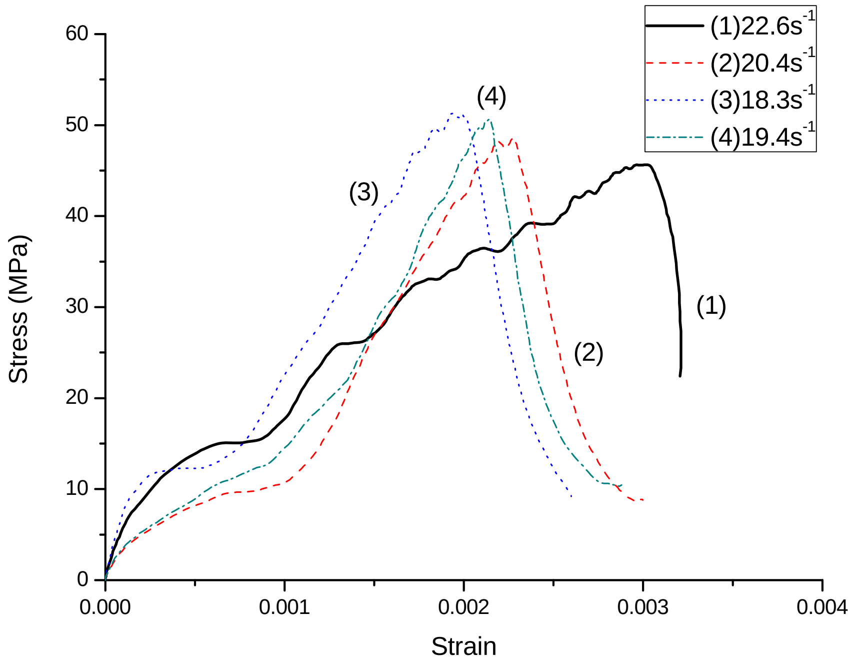


Fig. 7 Stress-strain curves of CRC-10 under different impact times

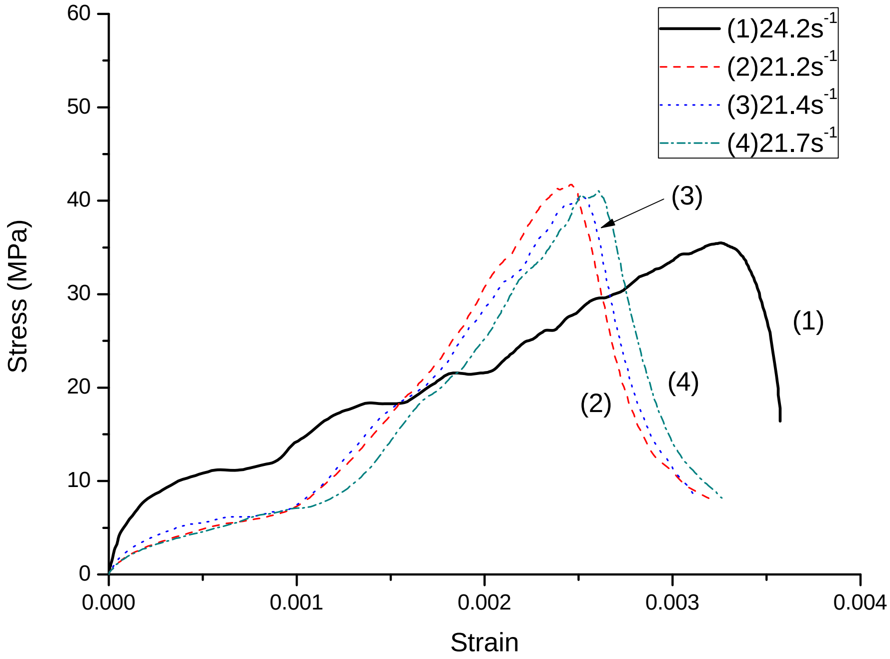


Fig. 8 Stress-strain curves of CRC-15 under different impact times

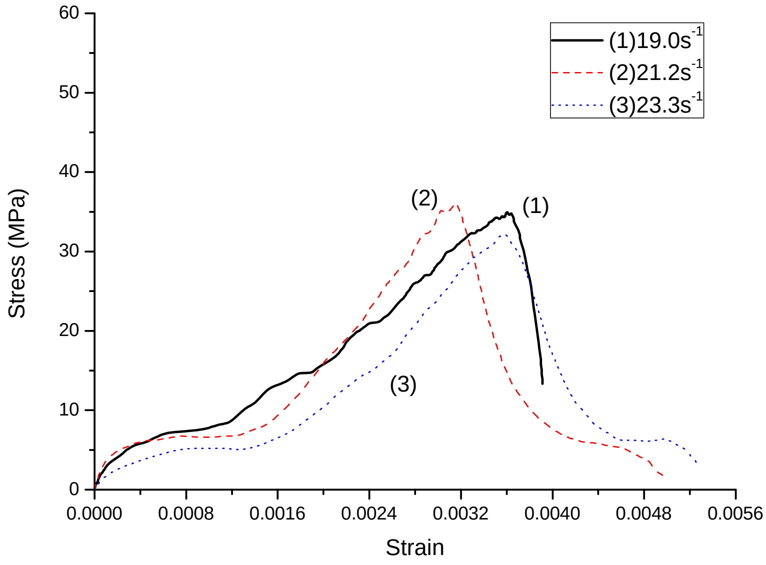


Fig. 9 Stress-strain curves of CRC-20 under different impact times

4. ANALYSIS OF FAILURE MODES

Fig. 10 clearly shows the failure mode of NC and CRC-10 influenced by repeated impact. Cylindrical specimens of NC split into two halves after two times' impact, and the two halves basically maintain their integrity. When crumb rubber is mixed into NC, repeated impact resistance of the material is significantly improved.

The first impact The second impact

(a) Failure mode of NC

The first impact The second impact The third impact The fourth impact

(b) Failure mode of CRC-10

Fig. 10 Failure mode of NC and CRC-10 under repeated impacts

It can be seen from the failure modes that the micro cracks emerge first at the edge of the cylindrical specimens of CRC, and then develop gradually to the central location. The randomly distributed crumb rubber can prevent the concrete from breaking and limit the micro crack propagation. The micro crack's development of CRC is much slower than that of NC's. Macro crack appears throughout the specimen after several impacts and cylindrical specimens of CRC break symmetrically into several pieces and each piece also maintain certainly integrity. From the point of view of final damage, CRC specimens is much more damaged than NC, it also indicates that the capability of energy absorption of CRC is much bigger than that of NC under repeated impact. Under the same impact times, the damage of CRC-10 is the least, RC is the most. The damage of CRC-15, CRC-20 and CRC-5 is in the moderate. Similar conclusion can be seen in paper of Topcu and Avcular (1997).

5. INFLUENCE OF RUBBER CONTENTS ON THE DYNAMIC PROPERTIES OF CRC

From Fig. 5 to Fig. 9 and Table 2 it can be seen that the ability of repeated impact resistance of NC is weak. The macro crack appears throughout the specimen after two times' impacts, and then the test can't be carried on. When the crumb rubber mixed into NC, repeated impact resistance of the material is significantly improved.

The cubic compressive strength values of CRC decreased with the increase of the amount of crumb rubber, which are 45.7 MPa, 40.9 MPa, 33.0 MPa, 28.1 MPa for crumb rubber addition of 5%, 10%, 15% and 20% respectively. When the rubber content is 20%, the strength of CRC is considerably decreased by 43.5%. In the SHPB tests, with the increase of the amount of crumb rubber, the peak stress decreases. However, the peak and ultimate strains increase. The times of repeated impact resistance increase at the beginning and then decreases. On the whole, the capability of energy absorption of CRC is higher than that of NC under repeated impacts when subjected to multi times repeated impacts. The peak stress of NC and CRC increase slightly, nevertheless the peak strain decrease slightly.

With the increase of the times of repeated impacts, a large number of micro cracks form and develop and the damage transition zone appears, so the energy dissipation increased and the instability development of the crack delayed, and the material's toughness increased. As is shown in Fig. 5 to Fig. 9, the stress-strain curves become flatter after the peak stress with the increase of the contents of crumb rubber, which indicates that the toughening effect of the addition of crumb rubber is obvious.

The impact resistance of the concrete is significantly improved when crumb rubber is mixed into NC. There may be some reasons for this. Firstly, the addition of a certain content of crumb rubber can fill void in concrete to improve the dense degree. Secondly, with the help of the cementation of cement, crumb rubber bonds with surrounding materials and forms a structural deformation center with certain intensity, which can burdens and absorbs parts of stress, eliminate the stress concentration of void, prevent the concrete matrix from breaking and limits the micro crack propagation, so the impact resistance of CRC is higher than that of NC.

6. CONCLUSIONS

In this paper, the experimental study is designed to investigate the influence of rubber contents on the dynamic properties of CRC subjected to repeated impacts by SHPB, the following conclusions can be drawn:

(1) The addition of rubber to CRC results in a reduction of concrete strength, the more the rubber added, the lower the concrete strength obtained. When the rubber content is 20%, strength is considerably decreased by 43.5%.

(2) In the SHPB tests, with the increase of the contents of crumb rubber, the peak stress decreases, the peak and ultimate strains increase, the times of repeated impact resistant increase at the beginning and then decreases. On the whole, the capability of energy absorption of CRC is more than that of NC under repeated impacts.

(3) Under the same impact times, the damage of CRC-10 is the least one among specimens. However, its compressive strength is not obviously decreased.

(4) With the increase of the amount of crumb rubber, the stress-strain curves become flatter after the peak stress, which indicates that the toughening effects of the addition of crumb rubber is obvious.

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