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Experimental study on dynamic split tensile properties of rubber concrete

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HIGHLIGHTS

- Sand was replaced by crumb rubber particles in concrete mixes at the volume ratio of 10–50%.
- The dynamic split tensile strength, strain-rate effect, and dynamic increase factor of NC and RC were studied.
- The optimal volume fraction of rubber particles that replaced sand under dynamic loads was obtained.

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ABSTRACT

Static and dynamic split tensile tests were conducted on rubber concrete with varied volume fractions of rubber particles that replaced fine aggregate (10%, 20%, 30%, 40%, and 50%, named as RC10, RC20, RC30, RC40, and RC50, respectively). The flattened Brazilian disc specimens were applied to determine the tensile properties and energy absorption capabilities under high strain rate by an SHPB (Split Hopkinson Pressure Bar) and medium strain rate by a drop-hammer testing machine. With a high-speed camera, the crack growth of specimens in the SHPB and drop-hammer impacting tests was observed and validated. The experimental result of five rubber concretes and one normal concrete without rubber particles was obtained, and the strain-rate effect on tensile strength of rubber concretes and normal concrete was confirmed. For high strain rate, RC10, RC20 and RC30 were sensitive to strain rate dependence, but rate dependence of RC40 and RC50 was lower than normal concrete. RC30 exhibited the most sensitivity and excellent energy absorption capability in static and dynamic tests. Excessive rubber content did not continually increase the toughness of the concrete under dynamic loadings.

1. Introduction

Concrete is a type of brittle material and the brittleness index increases with the strength grade of concrete. It was recently demonstrated that the toughness index [1–3] and durability [4–6] of concrete is enhanced by mixing with part of the reclaimed rubber powders. Additionally, the response of concrete materials subjected to high strain rate loadings is different from that under static loadings. Strain rate effect on normal concrete has been characterized by many studies [7–10]. Similarly, the existing research results [11–14] show that the compressive strength of rubber concrete has the same strain rate effect and the energy absorption capability of rubber concrete under dynamic loadings is better than normal concrete. While the tensile strength of the concrete materials is much weaker than the compressive strength, it is a necessary property of concrete. Malver [15,16] summarized the relationship between the strain rate and the tensile dynamic increase factor (DIF), which is the ratio of the dynamic tensile strength under different strain rate loads to static tensile strength.

Nevertheless, directly testing concrete for tension is complex, hence the International Society for Rock Mechanics (ISRM) and American Society for Testing and Material (ASTM) have advised that using Brazilian discs is a suitable method for testing the static tensile strength of rock [17] and concrete [18]. The Brazilian disc split tensile test has gradually been applied to dynamic mechanical tests of brittle materials. However, it is difficult to keep the disc motionless between the loading platen of a test machine and the circumferential surface of a specimen before the test, and it is easily subjected to concentrated stress at the contact point when the specimen being suffered impact loadings. The principle of

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Brazilian disc split tensile test is to ensure that the crack is initially produced at the centre of the disc. If the specimen cracks from the contact point instead of rupturing from the centre, the test is invalid. Awaji and Sato [19] used a pair of rounded load-bearing strips to solve these problems. This method was also applied to the dynamic Brazilian disc test [20,21]. In the above results, the size of strips varied and the match between the strips and the outer boundary of a disc specimen is difficult. Furthermore, Rocco et al. [22] verified that the split tensile strength of specimens is related to the size of load-bearing strips. Therefore, it is complicated to standardize the size and material of strips for test validity and accuracy. Wang et al. [23,24] determined the improved solution of polishing two parallel and smooth flat ends on the circular surface of a rock disc for the experiment, termed flattened Brazilian disc (FBD). FBD specimens not only avoid the stress concentration during the test but are also more convenient to prepare, and they accurate for the dynamic split tensile test. This method is also appropriate for concrete, which is as a brittle material. Hence, FBD specimens were applied in this paper to obtain the dynamic tensile properties of rubber concrete. For the accuracy of the test, a high precision grinder (MY250, Shandong Province, China), which has 0.01/300 mm parallelism accuracy and Ra0.1 μm fineness accuracy, was employed in this investigation to guarantee the requirements for precision of specimens.

Drop-hammer devices and Split Hopkinson Pressure Bar (SHPB), has been widely employed to study the dynamic properties of various materials at medium and high strain rates, respectively. For the dynamic properties of rubber concrete, there were two main methods for rubber particles mixed into the concrete, as partial replacement of fine aggregate or coarse aggregate. Topcu [25] was one of the first to characterize the dynamic compressive strength and the impact resistance of rubber concrete by drop-hammer test and found that rubber pieces replacing both coarse and fine aggregate added into the mixture have stronger plastic energy absorption capacity. Atahan et al. [26] simulated the crash between the vehicles and the New Jersey concrete barriers and it revealed that 20–40% coarse aggregate replaced by volume exhibited the best impact resistance. Khaloo et al. [27] studied the toughness of concrete specimens containing rubber as fine aggregate and found that 25% replacement is the maximum toughness. Khalil et al. [11] used a drop-hammer device to obtain the dynamic tensile properties at medium strain rates and found that replacing fine aggregate by volume over 30%, lowered the improvement of impact resistance instead, and the strength was unusually weakened. Whether as fine aggregate or coarse aggregate mix into concrete for rubber particles, the differences between the above results is small, the optimal content is around 20–30%. The principle reason for differences is the interval of the rubber's dosages are different. Additionally, rubber particles were generally made from waste tires. The particle size of them is usually small, which is close to the particle size of sand. Hence, rubber particles were replaced fine aggregate by most researchers. Recently, SHPB devices have gradually been utilized on rubber concrete to determine the dynamic compressive properties [12,13].

Because most components of concrete structures may fail due to tensile or shear stress, and few studies have investigated the strain rate sensitivity of tensile strength of rubber concrete. It is necessary to study the tensile properties under various dynamic loadings. Rubber particle replacement of fine aggregate was also applied in this investigation. The strain rate sensitivity of tensile strength on rubber concrete was verified by experimental techniques and compared with normal concrete in this study. The basic theories of the static and dynamic experiments are presented (in Section 2). The static split tensile properties and Young's modulus of rubber concrete were determined by experiments (in Section 3). The dynamic split tensile test on rubber concrete was conducted by a drop-hammer testing machine (Instron Ceast 9350) (in Section 4) and a Ø100 mm SHPB device (in Section 5) to characterize the dynamic tensile properties including dynamic tensile strength and energy absorbing capacity under various strain rate loadings. Finally, the optimal content of rubber and the dynamic tensile properties of rubber concrete were determined to promote the usage of the waste rubber (in Section 6).

2. Specimen preparation and experimental principles

This section details the basic theories of the static and dynamic experiments as a foundation for our investigation.

2.1. Mix proportion and specimen preparation

The specimens consisted of concrete, a mixture of PO42.5R cement, tap water, and medium sand with an average fineness modulus of 2.60 and a bulk density of 1221 kg/m^3 and coarse granite aggregate with a maximum size of 10 mm. The mass ratio of the four materials is 398:210:609:1183. The crumb rubber particles were in size of 20 mesh (around 0.85 mm) with a bulk density of 539 kg/m^3 and the volume fractions of sand replaced by rubber particles were 0%, 10%, 20%, 30%, 40% and 50%. After a curing time of 28 days, five rubber concretes and one normal concrete were prepared and named NC (normal concrete), RC10 (10%), RC20 (20%), RC30 (30%), RC40 (40%) and RC50 (50%), respectively. The mass ratio was calculated and summarized in Table 1.

2.2. Fundamental principle on static tests

2.2.1. Uniaxial compression test for elastic modulus of rubber concrete

For the uniaxial compression test, concrete specimens in the size of Ø150×300 mm cylinders were prepared. A compression-testing machine (Matest C088-01, Italy) was used to determine the elastic modulus of rubber concrete.

Before the test, four strain gauges were glued on the circumferential surface of the cylinders. Specimens were levelled by two longitudinal gauges to avoid eccentric compression or partial stress concentration under the testing machine, and two horizontal gauges were to measure the circumferential strains of the cylinders. The longitudinal gauges and the horizontal gauges had an electric resistance value of 120 ± 0.1 Ω, a sensitivity coefficient of 2.08 ± 1%, and the gauge lengths were 100 mm and 80 mm, respectively. Besides, two linear variable differential transformer (LVDT) transducers were applied to measure the relative longitudinal displacement, while the longitudinal strain was obtained by derivation. All the original data of strain gauges were acquired by using a static data acquisition device (TDS530, Japan). The loading rate of 0.18 mm/min (approximately $1 \times 10^{-6}\ \mathrm{s}^{-1}$ strain rate for Ø150 × 300 mm cylinders) was applied to the test.

The Young's modulus E and Poisson's ratio v were determined from experiments using Eq. (1), based on ASTM Standard C469 [28].

Table 1
Mix proportion of NC, RC10, RC20, RC30, RC40 and RC50.

	Mix proportion (kg/m^3)				
	Cement	Water	Sand	Coarse aggregate	Rubber particles
NC	398	210	609	1183	0
RC10	398	210	548	1183	27
RC20	398	210	487	1183	54
RC30	398	210	426	1183	81
RC40	398	210	365	1183	108
RC50	398	210	305	1183	134