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Mechanical and fatigue performance of rubber concrete

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HIGHLIGHTS

- Toughness of the concrete increases with the increase of rubber contents.
- Fatigue life of the rubber concrete complies with a two-parameter Weibull distribution.
- Fatigue equations of the rubber concrete were presented.
- Fatigue limit strength of the rubber concrete was obtained.
- Fatigue fracture of the rubber concrete experienced three transition phases.

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ABSTRACT

This study determines the mechanical and fatigue performance of rubber concrete, which consists of 0%, 5%, 10% and 15% of the selected rubber contents in terms of the fine aggregation in volume. The rubber particles used in the experiments are made of the recycled tire. The fatigue performance of 60 standardized rubber concrete specimens with various rubber contents was experimentally studied under the constant-amplitude cyclic loading condition. This study provided a solution of the fatigue life of the rubber concrete, which was in good agreement with the Weibull distribution. It also provided the formulation of the double logarithmic fatigue equations indicating the characteristics of the rubber concrete and predicted the ultimate fatigue strength of rubber concrete with various rubber contents. Furthermore, discussion on the mechanism of fatigue damage of the rubber concrete was also undertaken and the results suggested that the fatigue process leading to the internal damage of rubber concrete would consist of three development phases, i.e., the nucleation, stable state and instable state. Under certain stress levels, the fatigue life and dynamic strain of the rubber concrete are higher than those of the ordinary concrete, and they increase to some extent with the rubber contents. Under the same strength level, the fatigue performance of the rubber concrete is better than that of the ordinary concrete.

1. Introduction

During the last two decades, the possible usefulness of tire rubber particles in concrete and mortar has been investigated. Though most investigations about rubber concrete materials focused on using tire rubber particles as coarse aggregate in concrete, however, it has been suggested that scrap tires can be recycled into three major sizes: chipped rubber particles (size ranging between 13 and 76 mm) being used as coarse aggregate, crumb rubber particles being analogs to fine aggregate (size ranging between 0.075 and 4.75 mm), and finally ground rubber particles (size ranging between 0.15 and 19 mm) [1,2]. It has recently been suggested that tire rubber ash can also be used to enhance concrete microstructure [3]. Research works continued and some of the results reported in the published papers by Fattuhi and Clark [4] and Topcu and Avcular [5] at early 1990s. Over the recent years, there has been significantly growing interests in use of recycled tire rubber in highway engineering [6,7]. In overall, studies of the rubber concrete focused on the characterization of physical and mechanical properties [8,9], microstructure properties [10,11], dynamic performance, energy dissipation capacity [12,13], durability [14,15], and industrial applications [16]. Some studies reported a reduction in weight when fine crumb tire rubber was incorporated in the concrete mix. Compared with ordinary concrete, rubber concrete shows an obvious reduction in weight, compressive and tensile strengths, and static stiffness; on the other hand, a significant increase has been reported in impact resistance (toughness), the brittleness resistance, the strain capacity and thus the energy absorb ability, the workability, the impermeability, the thermal insulating ability, the freeze–thaw resisting performance and durability. Little research in the literature examined the fatigue characteristics of concrete incorporating rubber particles [17–19]. It is suggested that the rubber concrete could obtain the

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overwhelming prospects in engineering applications if appropriate proportion of the rubber and concrete was chosen. This would lead to desirable strength and fracture toughness criteria.

Furthermore, recycling of waste solid materials is becoming one of the global concerns with the continuously growing world population. Tire rubber contributes to a large proportion of solid waste and has caused growing global environmental problem. Since cement-based materials, particularly concrete, account for the largest part of the construction materials, integration of the waste tire into these materials represents a promising solution for reuse of such an industrial waste.

Unlike in asphalt mixes, use of tire rubber in concrete faces a challenge of lack of heat treatment, which is crucial to enable good adhesion between the tire rubber particles and other materials. Another challenge for this use lies in the potential mismatch in stiffness between the relative soft viscoelastic rubber and the relative rigid elastic cement-based matrix [20]. To tackle these challenges, this research undertook close experimental examination of the mechanical, fracture, and fatigue properties of the tire-rubber-particle impregnated concrete mixes, which acts as the replacement of the fine aggregate sand. Further, the research developed the possible ways of making concretes with the acceptable strength and other properties such as enhanced energy absorption and fracture toughness, by impregnating the tire rubber particles within the main mixture. Since fatigue performance is one of the most important aspects of the rubber concrete when being used as building materials [21,22], this research also attempted to disclose the fatigue life, fatigue equation, fatigue ultimate strength and fatigue damage mechanism of rubber concrete with different rubber contents.

2. Experimental study of mechanical and fatigue properties of rubber concrete

2.1. Material properties and mix proportions

The testing materials include: Portland cement with a compressive strength of 42.5 MPa (28-day); river sand with a fineness modulus of 2.40 and maximum size of 5 mm; crushed stone aggregate with sizes of 10–40 mm; water-reducing admixture with 30% of water reduction rate; and the rubber grain size of 2 mm. The net volume approach was applied to determine the proportions of the concrete components. During the process, the rubber ratio is set to 5%, 10%, and 15% in terms of volume of fine aggregate respectively. Mixture proportion of the rubber concrete is shown in Table 1.

2.2. Testing procedure

Based on the GB50152-92 Standard Methods for Testing of Concrete Structure [23] and GB50081-2002 Standard for Test Method of Mechanical Properties on the Ordinary Concrete [24] available in China, which are equivalent to the ASTM international, a total of 36 specimens were prepared and examined under the standardized conditions. The first three groups comprising 12 cubic specimens, each having the sizes of 150 mm × 150 mm × 150 mm, were prepared and put into cube compressive tests, by using the Digital Pressure Tester with the ultimate load of 3000 kN and loading speed of 0.5–0.8 MPa/s. The second three groups comprising 12 column specimens, each sized to 100 mm × 100 mm × 300 mm, were made and put into axial compressive tests, under the loading speed of 0.05–0.08 MPa/s. By multiplying the size conversion coefficient of 0.95 as addressed in the above Chinese standards, the tested results could be converted into the actual axial compressive strength. The third three groups comprising 12 beam specimens each with sizes of 150 mm × 150 mm × 400 mm were also prepared and put into flexural testing. By multiplying the size conversion coefficient of 0.85 as addressed in the Chinese standards, the tested results could be converted into the actual ultimate and deflection load, which was obtained at loading speed of 0.05 mm/min.

Table 1
Proportion of mixture of rubber concrete with different rubber contents.

Type	Material (kg/m^3)					
	Water	Cement	Sand	Gravel	Rubber	Water reduce
RC-0	131.5	420	555	1296	0	5.0
RC-5	131.5	420	527	1296	11.68	5.0
RC-10	131.5	420	500	1296	22.95	5.0
RC-15	131.5	420	472	1296	34.66	5.0

The sizes of the standard specimen for flexural and fatigue testing are 150 mm × 150 mm × 550 mm. The three-point bending fatigue tests with a 400 mm span were carried out on the specimens using a 500 kN electro-hydraulic servo testing machine. These specimens were subjected to uniform pulsation loads with constant amplitude (the maximum load $P_{\max}$ and minimum load $P_{\min}$ are kept constant); the load-control mode and a constant load ratio of 0.1 (load cycle characteristics $\rho = P_{\min}/P_{\max} = 0.1$) were adopted in this experiment. During this process, the loading frequency was chosen as 5 Hz, which is at reasonable frequency range and has no obvious effects on fatigue strength of specimens with regard to the performance of the testing machine.

Four load levels were applied in this study in order to investigate the fatigue performance of the rubber concrete with different rubber contents and under different load levels. The load level $S = P_{\max}/P_0$ was set to 0.9, 0.8, 0.7 and 0.6 respectively, in which $P_{\max}$ is the maximum load acted on the specimens, and P_0 is the average value of the peak loads of the rubber concrete beam. Table 2 presents the rubber contents, load levels, load frequencies and load types applied in the tests.

Prior to the fatigue testing, the beam was put onto the 1 kN of preload twice in order to eliminate the error caused by poor contact and ensure appropriate instrumental operation. The standard load was then added into the value of P_m which has the average value of the fatigue loads under testing. The fatigue testing was further carried out when the load remained at the steady state condition; while the load amplitude was adjusted to allow the load frequency to be fixed to 5 Hz and the maximum number of cycles set to 2 × 107. The testing was finished when the specimen was destroyed or the loading cycles reached the maximum cyclic number.

2.3. Tested results of mechanical properties

The tested results for the weight, apparent density, cube strength and flexural strength of specimens are presented in Table 3. It is found that the apparent density, cube strength, axial compressive strength and the flexural strength decreased with the increase of rubber contents, the greater the contents of rubber, the greater the extent of decline. In this case, the apparent density and cube strength of the ordinary concrete (RC-0) were 2459 kg/m^3 and 57.8 MPa, respectively, whilst the flexural strength was 5.6 MPa. The reduction rates of the compressive strength and flexural strength for the rubber concrete are 12.5%, 21.6%, 34.8% and 5.4%, 8.9%, 17.8% respectively, in accordance with the rubber powder contents of 5%, 10%, 15%. The decline rate of the compressive strength is twice that of the flexural strength, which was similar to the results in the literature [9]. The reduction of compressive strength of the concrete incorporating tire rubber particles can be attributed to three reasons: firstly, the deformability of the rubber particles against the surrounding cement paste, which resulted in initiating cracks around the rubber particles in a similar way to what occurring in the ordinary concrete with the air voids. Secondly, the weak bond between the rubber particles and the cement paste. Finally, the possible reduction of the concrete matrix density which largely relied on the density, size, and hardness of the aggregate. The ratio of the flexural strength to the compressive strength of the rubber concrete with 5%, 10% and 15% rubber contents was 1.08, 1.16 and 1.26 times those of the ordinary concrete respectively, indicating that rubber concrete has superior anti-cracking performance against the ordinary concrete.

2.4. Three-point flexural test

The three-point flexural testing was undertaken to determine the ultimate fracture load of the rubber concrete. The testing beams were 100 mm in width, 100 mm in depth and 550 mm in length. During the bending process, the loading span was 400 mm.

The tested results of the load–deflection (F–δ) and load–strain (F–ε) are shown in Figs. 1 and 2. The peak values of the load, deflection and strain are presented in Table 4. It is found that the peak deflection of the rubber concrete was higher than that of the ordinary concrete, e.g., 1.33 mm for 15% contents which is 2.4 times that for the ordinary concrete. Furthermore, the ultimate tensile strain of the rubber concrete under flexure is 1.62, 2.25 and 2.80 times those for the ordinary concrete, respectively. The results show that the rubber can effectively absorb the deformation energy of the expansion cracks, and thus is capable of improving the toughness and reducing the brittleness of concrete.

It is found, from the load–deflection and load–strain curves, that increasing the rubber contents led to growing area under the curves, which indicates that the rubber can effectively absorb the released energy from deformation propagation.

2.5. Fracture failure analysis

The compressive and flexural strength of the concrete decreased with increasing of the rubber contents. In this case, the specimens of the rubber concrete were still in good shape at the ultimate compressive or flexural load bearing conditions, while specimens for the ordinary concrete were sharply chipped. Figs. 3–5 presented the failure forms for different rubber concrete.