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Experimental study on dynamic mechanical properties of the basalt fiber reinforced concrete after the freeze-thaw based on the digital image correlation method

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HIGHLIGHTS

- This paper studies the effect of basalt fibers and FTCs on the concrete impact resistance.
- Adding fibers could significantly improve the impact resistance of the concrete.
- The FTCs made the basalt fibers lose its enhancement effect.

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ABSTRACT

This paper studies the effect of the basalt fibers and the freeze thaw cycles on the concrete impact failure mechanism through the concrete beam fall ball impact test. The experiment used the digital image correlation method to measure the full field strains and then make a real-time analysis of them. Based on the number of impacts and the strain curves of the starting crack points, the impact times respectively for initial cracking and eventual damaging were determined. The test results show that with the basalt fiber content increasing, the impact times for the concrete specimens' initial cracking and final failure were also raised because adding fibers formed a three-dimensional system which could enlarge the transmission range of the impact stress waves and thus improved the concrete's elastic deformation performance, that is, improved the concrete's initial cracking capability to impact resistance. On the other hand, as the number of freeze-thaw cycles increased, the impact times for the initial crack and the final failure declined in that the freeze-thaw damage reduced the elastic deformation performance of the concrete specimens. The impact energy in the early freeze-thaw period lost the fastest and the most, indicating that the freeze-thaw cycles would produce damage and defect in the fiber/matrix interface and therefore made the fiber's three-dimensional system gradually lose its enhancement effect. The experimental study provides a new approach to understanding the effect of the fibers and the freeze-thaw cycles on the impact resistance performance of the concrete.

1. Introduction

The fiber reinforced concrete (FRC) has been developing rapidly in recent years as a new type of cement base composite and has been successfully applied in the field of military works, water conservancies, construction of buildings, airports, and high ways owing to its excellent tensile an bending strength, crack and shrinkage resistance, impact resistance, anti-permeability, and frost resistance. Fiber reinforced materials include steel fibers, synthetic fibers, basalt fibers, carbon fibers, hybrid fibers, etc. Researchers have conducted some tests to study the dynamic mechanical properties of various FRC materials under room temperature [1–6] and have found that fibers can effectively improve the brittleness of the concrete and thus improve its resistance to the impact load. However, in cold regions the concrete members are not only affected by such dynamic loadings as impact, vibration and collision, but also affected by the loading of freeze-thaw cycles [7], which may lead to the change of the internal structure of the material and the decline of its mechanical performance index [8–9]. Therefore, when calculating the structure design and

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analyzing the damage effect, the freeze-thaw damage degradation effect has to be considered apart from the impact damage effect of the dynamic loadings; otherwise the safety problems may arise by overestimating the bearing capacity of the material. In addition, to get familiar with the dynamic response properties of the FRC under freeze-thaw conditions is of great importance for evaluating the structure damage repair and expanding its application to a much wider range.

At present, further research needs to be done to represent the real-time mechanical performance and micro-macroscopic failure mechanism of the FRC under the freeze-thaw environment. As to the mechanical performance test under the freeze-thaw cycles, the material deformation test is one of the most difficult. The traditional strain gauge method is only able to measure the single direction deformation and the displacement at specific directions, but fails to attain the full-field strain information of the sample surface, and the strain gauge is also easy to fail under freeze-thaw cycles. The traditional fall ball impact test defines the initial crack impact times as the impact times that make the specimen produce microfractures when the strain gauge is placed at the bottom of the specimen, namely, the impact times when the concrete strain mutation occurs at the specimen's bottom [10]. However, it has been found in the experiment that after some specimens are subject to impacts, the strain value of the gauge gradually increases but the mutation does not occur even when the specimen is completely damaged. As a consequence, the number of the initial crack impact times cannot be measured. This is because, on the one hand, the crack position cannot be accurately predicted, so the crack does not go through from where the strain gauge is placed, and on the other hand, the freeze-thaw and the impact lead to the decline of the strain gauge bonding strength so the deformation cannot be accurately transferred to the gauge.

The digital image correlation method (DICM) uses modern optical technique to measure the mechanical full-field deformation with non-contact and high precision. It has been widely applied to engineering due to its simple operation, low demand on the specimen surface treatment, automatic and precise measurement [11–13]. In recent years, some researchers have used the DICM to study the mechanical properties of concrete and rock and have gained some achievements. Literature [14] applied the DICM to test the deformation in the concrete fatigue experiment and obtained the distribution of the displacement field and the strain field under the fatigue load, and therefore predicted the fatigue cracking up location and made a qualitative judgment of the performance degradation of the concrete specimen under the fatigue load. Literature [15] used DICM to study the strain field of the concrete precast crack tip region, observed the crack propagation process and area, and calculated the fracture toughness of the material. Literature [16], by means of DICM, measured the crack tip evolution process of the three-point concrete bending beam and obtained the crack tip displacement field and strain field of the specimen under different loads. Literature [17,18] attempted to use DICM to study the deformation of rocks with microscopic cracks, and found out that the displacement distribution obtained was closely related to the distribution of the microscopic cracks, showing the opening up or closing effect of the microscopic cracks in the rock damage. The above researches reveal that the DICM provides an effective experimental method for further study on the material and structure fracture damage.

Based on the DICM and the three-point bending drop impact test, this paper conducted a real-time observation of the full field strain of the concrete beam specimen in the process of impact fracture, and determined the initial crack impact times through the changing patterns of the strain at the cracking points. It also studied the mechanical impact properties and the damage evolution characteristics of the concrete with different basalt fiber contents and different freeze-thaw cycles, and discussed how the fiber incorporation and the freeze-thaw damage affected the concrete impact damage

2. Experiment

2.1. Testing method

The digital image correlation method employs CCD camera to record the respective speckle images before and after the displacement or deformation of the tested object to get two digital gray level fields by analog digital conversion and then some correlation calculations are operated to find the extreme value points of the correlation coefficient and obtain the corresponding displacement or deformation [16].

In the correlation computation, the gray level of the pixel contains the displacement information, so the correlation method is based on the gray level matching. Hence, it is necessary to set up a mathematical model to measure the image matching degree before and after the deformation. The formula is as follows.

$$C = \frac{\Sigma(f_i(x,y) - \bar{f}) \cdot (g_i(x^*,y^*) - \bar{g})}{\sqrt{\Sigma(f_i(x,y) - \bar{f})^2 \cdot \Sigma(g_i(x^*,y^*) - \bar{g})^2}} \tag{1}$$

Here, C is the correlation coefficient; $f\,(x, y)$ and $g\,(x* \; y*)$ represent the two gray level image subareas before and after the deformation. Due to the random speckle distribution, the spots distribution in the small area around each point of the object is different and this small area is usually referred to as the subarea. By searching the peak value of the correlation coefficient C we can determine the displacement both in direction X and direction Y for the target point and further obtain the strain change by numerical differential operation. In actual operation, the closer the correlation coefficient is to 1, the more reliable the displacement computed; otherwise, the closer the correlation coefficient is to 0, the greater the calculation error for the displacement.

2.2. Specimen preparation

The strength of the standard concrete used in the test is C30, whose mix proportion is listed in Table 1. The size of the specimen is 40 mm × 40 mm × 160 mm. In order to study the strengthening and toughening effects of the basalt fiber on the concrete, with the standard concrete mix proportion unchanged, different fiber contents were added into the concrete, respectively, 0.0 kg/m^3, 1.0 kg/m^3, 1.5 kg/m^3, 2.0 kg/m^3 and 2.5 kg/m^3. The physical and mechanical properties of the basalt fiber are illustrated in Table 2.

In the process of specimen preparation, the dry mix of sand, stone, cement, and basalt fibers was put into the mixer to stir for 3–5 min so that the fibers could mix well with the cement, sand and stone. Then water was added, stirring again for a while. In order to avoid the continuing increase of the intensity during the freeze-thaw caused by the short curing time, the experiment adopted the standard long time curing, namely, 120 days.

2.3. Testing method

The freeze-thaw cycling test used the "quick freeze method" specified by the national standard GB/T 50082-2009 [19] to freeze and thaw the specimen. The actual time for one freeze-thaw cycle lasted 3.5 h and the maximum and minimum central temperature of the specimen were respectively controlled at 8 ± 2 °C and −17 ± 2 °C. The fall ball impact test was conducted after the specimens had respectively undergone 15, 30, 45, 60 and 75 freeze-thaw cycles.