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Study on bending damage and failure of basalt fiber reinforced concrete under freeze-thaw cycles

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HIGHLIGHTS

- A damage degree factor and a localization factor were proposed.
- Fiber can improve the bending strength while freeze-thaw cycle can decrease it.
- Both fiber and freeze-thaw cycle change the bending failure into the ductility mode.

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ABSTRACT

The whole-field deformation of the basalt fiber reinforced concrete under three-point bending test were measured by the digital image correlation (DIC) technique. Based on the horizontal strain field on the specimen's surface, a damage degree factor and a localization factor were proposed to describe the bending damage and failure characteristics of the specimens, with a further analysis of the effect of the fiber content and freeze-thaw cycles on the characteristics. The experimental results show that the failure process can be divided into three stages: the micro-fracture dispersion, the macro-crack selection, and the main crack propagation. The basalt fiber extended the nonlinear phase of the curves characterizing the two factors, indicating that the fiber enhanced the resistance to the elastic-plastic deformation and thereby restrained the bending damage and failure. The freeze-thaw cycles shortened the linear phase of the two factor curves, suggesting that the freeze-thaw could reduce the elastic deformation capacity of the specimen and thereby accelerate the bending damage process. The incorporation of fibers can reduce the influence of freeze-thaw on the damage and failure process of the specimen, and in this test, the best bending performance of the basalt fiber concrete is given by concrete with 2.0 kg/m^3 basalt fiber density, but the freezing and thawing will weaken the role of fiber to inhibit the damage. Both the fiber incorporation and the freezing and thawing can change the bending damage process from the brittle failure to the ductile failure. However, in this process, the fiber incorporation can improve the bending strength of the specimen while the freeze-thaw can reduce the strength.

1. Introduction

The freeze-thaw damage is one of the major factors which will affect the endurance of the concrete structure. It makes the internal structure of the concrete loose and deteriorated and therefore weakens the mechanical property of the material [1,2]. Research has shown that adding fibers into the concrete can improve its freezing resistance. On the one hand, fibers can inhibit the formation and development of the cracking, thus enhancing the matrix strength. On the other hand, adding fibers can increase the number of harmless pores which can relieve the freezing pressure and therefore reduce the damage degree of the concrete caused by freeze-thaw [3–5]. The basalt fiber, as a new type of concrete reinforced material, is characteristic of low cost, good compatibility with the concrete matrix, superior mechanical property, strong corrosion resistance and environment friendly merit in its production [6]. More and more studies have been conducted on the improvement of the concrete's anti-freezing property by incorporating basalt fibers and some achievements have been obtained [7,8].

At present, the strength loss rate and the relative dynamic elastic modulus are often used to evaluate the freeze-thaw damage of the concrete [1,9], both of which, however, are average indexes to

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describe the concrete's overall strength and deformation performance. They can reflect the damage of the concrete components on the whole but fail to reflect how the freezing and thawing influences the whole damage process of the concrete components.

Digital Image Correlation (DIC) method can be used to test the displacement field and the strain field on the material surface during deformation. The method is easily operated with high precision, so it is widely applied in various engineering measurements. In recent years, DIC has been introduced into concrete studies, mainly on its deformation [10,11] and crack propagation [12,13], since the method is able to obtain the data of the whole field displacement and strain in real time. The concrete failure is characterized by the occurrence of deformation and fracture, and therefore much attention has been attached to the analysis of the damage process by using real-time optical deformation data.

The study, combining the DIC method and the concrete bending experiment, observed the deformation field of the failure process of the basalt fiber reinforced concrete after freezing and thawing in real time, illustrated the bending damage performance of the concrete by statistical strain analysis, and further discussed the influence of freeze-thaw and fiber incorporation on the damage and failure of the concrete.

2. Measuring principle

The principle of DIC method is to trace the movement of different points on the specimen's surface by analyzing the features of the randomly distributed speckles so as to acquire the deformation information of the surface. The gray level of the reference subset before the specimen's deformation is marked as f(x, y). After the deformation, the predefined correlation function is used to search in the gray image the area that best matches the gray level of the reference subset. If the correlation function approximates to the maximum value 1 or the minimum value −1, it means high similarity and the corresponding area can be taken as the target subset g(x′, y′). The displacement after deformation can be obtained by the corresponding relationship of the reference subset and the target subset, and then differential calculation is operated to the displacement values of different points so as to get the specimen's strain field.

Correlation function is key to determining the similarity of the reference subset and the target subset and it is the base of the DIC technique, so the function chosen has to be simple with small computational complexity and good anti-interference. This study chose the standardization covariance of cross-correlation function:

$$C(p) = \frac{\sum[f(x,y) - f_m][g(x',y') - g_m]}{\sqrt{\sum[f(x,y) - f_m]^2}\sqrt{\sum[g(x',y') - g_m]^2}} \tag{1}$$

where f_m and g_m respectively refer to the average value of the gray level for the reference subset and the target subset, and p is the deformation parameter vector, describing the position and shape of the target subset after deformation.

3. Testing procedures

3.1. Material and specimen preparation

Raw material: 42.5 ordinary Portland cement, natural washed river sand as fine aggregate with the fineness modulus of 2.45, continuous graded gravel with the diameter of 5 mm to 16 mm as coarse aggregate, tap water, 18 mm long chopped basalt fiber with the diameter of 15 μm.

The compressive strength of concrete cubes used in the test is 30 MPa. According to JGJ 55-2011Ordinary Concrete Mix Proportion Design Specification, the water cement ratio of the specimen is 0.5, the sand ratio is 0.35, the ratio of cement, water, sand and gravel is 1:0.5:1.475:2.74. According to GB/T 50081-2002 Standard for Test Method of Mechanical Properties of the Ordinary Concrete, after removing the mold, the specimens should be immediately placed into the standard curing room with the temperature of 20 ± 2 °C and the relative humidity above 95%. The standard curing age is 28 days. The fiber contents is respectively 0.0 kg/m^3, 1.0 kg/m^3, 1.5 kg/m^3, 2.0 kg/m^3, 2.5 kg/m^3. The size of the specimen is shown in Fig. 1.

3.2. Testing method

The test used quick freezing method with a freeze-thaw cycle of 3.5 h. The minimum and maximum center temperature of the specimen were controlled at −17 °C ± 2 °C and 8 °C ± 2 °C, and the number of freeze-thaw cycles is 0, 15, 30, 45, 60, 75.

Three-point bending tests were conducted on the specimens undergoing different freeze-thaw cycles. Model WDW-10 microcomputer control universal testing machine was used for loading. The displacement control rate of the loading process was 0.5 mm/min.

During loading, the DIC testing system recorded the deformation process of the specimen, as shown in Fig. 2. The speckle images on the surface of the specimens were captured by the CCD camera and sent back to the image collection card. In the later stage of the test, the speckle images were computed by the image analysis system to obtain the displacement and strain on the specimen's surface.

For the CCD camera used in the test, the maximum resolution is 1624(H) × 1224(V) pixels, the fastest frame rate is 30 fps and the strain precision is a value of 50 με or less. We set the CCD camera to serially record one picture every 200 ms. The black matted paint was used in order to obtain a speckle pattern with good contrast, uniform size and rich details. For the optimal subset size suggested by the DIC analysis software, the resolution precision can reach 0.1 pixels and the displacement precision is about 0.78 μm under, which meets the test request.

4. Results analysis

4.1. The bending damage process

In the process of loading, the horizontal strain field on the specimen's surface measured by DIC varied obviously, so the study chose the specimen without fibers and freeze-thaw to record the horizontal strain cloud corresponding to the six typical moments of A ~ F during loading, and then these clouds were analyzed with the load deflection curve as shown in Fig. 3.

Microfracture dispersion phase: In the initial stage of loading (point A), at the upper part of the horizontal stain cloud there is a much larger blue zone which represents the compression strain,

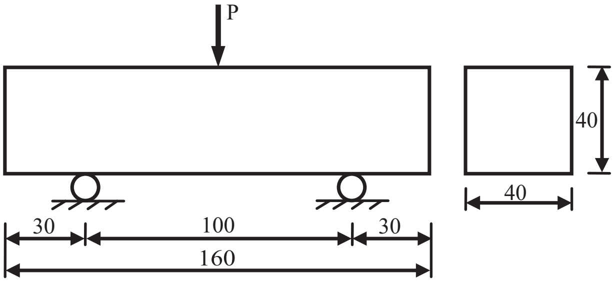

Fig. 1. Specimen geometry (unit: mm).