Research Article

An Experimental Study on the Compressive Dynamic Performance of Rubber Concrete under Freeze-Thaw Cycles

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An experimental study was conducted using a hydraulic servo machine to examine the compressive dynamic performance of rubber concrete under freeze-thaw cycles by considering 4 different numbers of freeze-thaw cycles and 8 different strain rates. The compressive stress-strain curves of rubber concrete under different loading conditions were obtained. By comparatively analyzing the mechanical characteristic parameters of the compressive stress-strain curves (i.e., peak stress, elastic modulus, and peak strain), the following conclusions were drawn: at the same loading strain rate, the compressive peak stress of rubber concrete is gradually decreased while the mass loss rate is gradually increased, as the number of freeze-thaw cycles increases. Compared to ordinary concrete, rubber concrete has a better frost resistance property. At the same number of freeze-thaw cycles, the compressive peak stress and elastic modulus of rubber concrete are gradually increased as the loading strain rate increases. The increase in the number of freeze-thaw cycles enlarges the increasing amplitude of the peak stress and elastic modulus under the action of loading strain rate. The compressive peak stress and elastic modulus dynamic increase factors of rubber concrete exhibit a linear relationship with the dimensionless logarithm of the loading strain rate. Meanwhile, a calculation model was proposed for the compressive peak stress dynamic increase factor of rubber concrete under the coupling effect of freeze-thaw cycles and loading strain rate, and the corresponding stress mechanism was discussed in detail. The research findings are of great significance to the application and development of antifreeze concrete in engineering practice.

1. Introduction

As one of the most widely used construction materials, the durability of concrete has long been an important concern in the field of concrete research; particularly, freeze-thaw cycle is considered the main factor in the deterioration of concrete materials [1–3]. In engineering practice, concrete may be undergoing a variety of dynamic effects such as earthquakes, impacts, and even explosions. Since concrete has an apparent strain rate effect, it is of great significance to examine the mechanical properties of concrete by considering the coupling effect of freeze-thaw cycles and strain rate [4, 5].

In order to improve the frost resistance property of concrete, a certain amount of air-entraining agent would usually be added to the concrete mixture. Relevant literature has reported that adding an appropriate amount of rubber particles into the concrete mixture can also effectively improve the frost resistance property of concrete, where rubber particles are equivalent to the solid air-entraining agent [6–8]. Among the research aiming at the effect of freeze-thaw cycles on rubber concrete, Paine et al. [9] examined the frost resistance of concrete specimens mixed with rubber particles of varying sizes. Their findings showed that rubber particles could significantly improve the freeze-thaw
resistance of concrete and the frost resistance of rubber concrete was comparable to that of concrete mixed with air-entraining agents. Savas et al. [10] added rubber particles (particle size: 2–6 mm) into concrete specimens at 10%, 15%, 20%, and 30% of the mass of cement and carried out a quick-freezing experiment. The results implied that the frost resistance of concrete containing 10% and 15% rubber particles was greatly improved. Topcu et al. [11] prepared concrete specimens containing 1–4 mm rubber particles at 10%, 20%, and 30% of the volume of aggregate and conducted a freeze-thaw cyclic experiment. The results showed that the frost resistance of all the concrete specimens containing rubber particles was better than that of specimens without rubber particles. Benazzouk and Queneudec [12] used compressed rubber aggregate (RCA) and expanded rubber aggregate (ERA) to replace the original aggregate components in the concrete. Their results showed that the frost resistance property of concrete was significantly improved when the volume replacement rate reached 30%–40%, and ERA had a better improvement effect than CRA. Targeting the dynamic performance of concrete, the literature [13–15] conducted experimental research and theoretical analysis from the perspectives of loading method, material type, and stress environment. Its main findings include the following: (1) the peak stress of concrete is gradually increased as the loading strain rate increases; (2) the effect of loading strain rate under tension is stronger than that under compression; (3) when the loading strain rate is higher than 10/s, the increase in peak stress caused by strain rate is more obvious; (4) the various environmental effects have significant effects on the dynamic performance of concrete. The literature [16] established the dynamic constitutive relationship of concrete from the perspective of the elastoplastic damage theory. The literature [17] examined the dynamic performance of ordinary concrete under the action of different numbers of freeze-thaw cycles and found that the dynamic performance of concrete was significantly affected by freeze-thaw cycles. Feng et al. [18] carried out an experimental study on the dynamic split-tensile mechanical properties of rubber concrete with different replacement rates under high strain rates, and the results showed that rubber particles had a significant effect on the dynamic characteristics of the concrete. Xu et al. [19] examined the monotonic compressive and cyclic compressive mechanical properties of rubber concrete under the action of seismic magnitude strain rates and proposed the mathematical relationship between the coupling effect of rubber content and strain rate and the unloading stiffness and residual strain. Alsaf et al. [20] studied the mechanical properties of steel fiber rubber concrete under freeze-thaw cycles, and the results showed that the addition of a certain amount of steel fibers could improve the performance of the concrete. Richardson et al. [21] examined the mechanical properties of rubber concrete under freeze-thaw cycles and found that rubber particles could improve the mechanical properties of concrete during freezing and thawing. On such basis, the authors proposed the rubber particle size, which could constitute rubber concrete with a better antifreezing property. All the aforementioned studies considered improving the antifreezing property of concrete by adding admixtures and examined the dynamic performance of rubber concrete. However, no research has been conducted yet on the dynamic performance of rubber concrete under the effect of freeze-thaw cycles. The research focusing on rubber concrete under the coupling effect of freeze-thaw cycles is of great significance to the analysis of the dynamic performance of rubber concrete structures in severe cold areas. Therefore, it is necessary to carry out experimental studies on the dynamic performance of rubber concrete under the action of freeze-thaw cycles.

In this paper, an experimental study was carried out using a hydraulic servo machine to examine the compressive dynamic performance of concrete with a replacement rate of 10% rubber particles under the action of freeze-thaw cycles. A total of 4 different numbers of freeze-thaw cycles and 8 different loading strain rates were considered. Through the experiment, the compressive stress-strain curves of rubber concrete under different loading conditions were obtained and comparatively analyzed in terms of mechanical characteristic parameters (i.e., peak stress, elastic modulus, and peak strain). The results were used to examine the coupling effect of freeze-thaw cycles and strain rate on rubber concrete. The conclusions of this study will provide a theoretical basis for the research of antifreeze concrete and its applications in engineering practice.

2. Experiment

2.1. Specimen Mix Proportion Design. In view of the purpose of this study, the strength of concrete without rubber particles was designed to be 30 MPa according to applicable concrete design specifications. Based on the conclusions of relevant literature [8-9] on the impermeability and frost resistance of rubber concrete, it was expected that rubber concrete had good impermeability and frost resistance when the rubber replacement rate was ranged 10%–15%. Therefore, in this study, the replacement rate of rubber particles was determined to be 10% by volume. Part of the fine aggregate in the concrete was replaced by the same volume of rubber particles so as to calculate the mix proportion of rubber concrete. Specifically, the masses of cement, water, fine aggregate, rubber particles, and coarse aggregate required for each cubic of the concrete mixture are 279 kg, 178 kg, 702 kg, 32.3 kg, and 1034 kg, respectively. For the various raw materials, the cement is ordinary Portland cement PO 42.5, and the chemical composition of cement is shown in Table 1. The apparent density of the fine aggregate and coarse aggregate is 2650 kg/m$^3$ and 2580 kg/m$^3$, respectively. The fineness modulus of fine aggregate is 2.5, and the particle size of coarse aggregate ranges 4–16 mm. The rubber particles used in this experiment have a particle size of 2–5 mm, a fiber content of ≤0.1%, and an apparent density of 1270 kg/m$^3$. The tensile strength and breaking elongation of the rubber particles are >15 MPa and >500%, respectively.

Pour the weighed cement, fine aggregates, and rubber particles into the mixer. After thorough stirring, add coarse aggregates into the mixer. After thorough stirring again, pour the weighed water slowly into the mixer and stir the
mixture evenly. Then, pour the rubber concrete mixture into the mold and place the mold on a vibrating table to vibrate until compact. Demolded one day later and place the specimen in a standard curing room (temperature 20 ± 2°C, humidity 95%) for 28 days before using it for the experiment. The slump of the rubber concrete mixture with a 10% rubber particle replacement rate is 23 mm, and the mass of the specimen is slightly lower than that of ordinary concrete.

2.2. Experiment Plan. The specifications of concrete freeze-thaw cyclic experiment highlight that the concrete specimens need to be saturated before proceeding with the experiment. In this study, all the specimens were saturated by sinking them into water. The specimens would be weighed repeatedly during this period until their masses became basically unchanged. That is, the saturation state was reached. Then, the concrete specimens were placed into a freeze-thaw cyclic machine for periodic freezing and thawing. After reaching the predetermined number of freeze-thaw cycles, the specimens would be taken out and smoothened with mortar to avoid the potential problem that the specimen cannot be fully axially stressed during the loading process. In this study, the number of freeze-thaw cycles was designed to be 0, 50, 100, and 150 (indexed as D-0, D-50, D-100, and D-150, respectively) [22]. According to the “Standard for test methods of long-term performance and durability of ordinary concrete (GB/T 50082-2009),” the center temperature of the rubber concrete specimen ranges between -20°C–20°C, and one freeze-thaw cycle takes 3 hours. The conversion time between freezing and thawing should not exceed 10 minutes, and the thawing time should not be less than 25% of the entire freeze-thaw cycle [22]. The equipment for the freeze-thaw cycle test is shown in Figure 1(a). Before the test, the specimens were immersed in water for 4 days until saturation. During the entire freeze-thaw cycles, the specimens would remain at a saturated state, and the water level in the specimen container was maintained about 5 mm higher than the top surface of the specimen. According to “Standard for test methods of long-term performance and durability of ordinary concrete (GB/T 50082-2009),” a concrete specimen with exactly the same size and shape as the test specimen was made. A temperature sensor was embedded at the center of this specimen to measure the temperature of the center area.

A material single-axis hydraulic servo machine was used to examine the compressive dynamic performance of rubber concrete under different numbers of freeze-thaw cycles. This machine is equipped with independent load sensors and deformation sensors. The ranges of load and displacement measurement and the precision of sensors are compliant with the experimental requirements. Referencing the sizes of specimens used in the existing literature, the specimen size in this study was determined to be 100 mm cube. In the present study, cube specimens were used to obtain the compressive stress-strain curve mainly due to the following reasons: (1) the “Standard for test methods of long-term performance and durability of ordinary concrete (GB/T 50082-2009)” recommends the use of 100 mm cube specimens as the standard test specimen. (2) The relevant literature [13, 14, 23] uses cube specimens as the approximate research object for examining the uniaxial mechanical properties of concrete. From a qualitative point of view, it can meet the requirements of test analysis to a certain extent to obtain the basic mechanical properties. In view of the impact of the randomness and discreteness of concrete materials on the experimental results, 3 valid specimens were prepared and tested for each working condition, and the mean value was computed for analysis. The loading device is shown in Figure 1(b).

To examine the dynamic performance of rubber concrete under different numbers of freeze-thaw cycles, the compressive dynamic loading was realized through loading strain rate. Each loading strain rate corresponds to a different magnitude of dynamic action. In this paper, 8 different loading strain rates were designed according to earthquake-magnitude dynamic actions. Specifically, the lowest compressive loading strain rate is 10⁻³/s (static loading strain rate), while the highest compressive loading strain rate is 5 × 10⁻²/s, as shown in Figure 2 [23]. The compressive load control consists of two types of control: load control and displacement control. The load control mode was applied first until reaching 5% of the designed strength and then unloaded. This loading-unloading process would be repeated three times to control the gap between the equipment loading surface and the specimen surface. Then, the formal loading process would be initiated by adopting the displacement control mode at a loading speed corresponding to the designed strain rate. The loading process would continue until the specimen failed. The friction at the loading surface was controlled by applying the method described in the literature [13], which is compliant with the experimental requirements of this study.

3. Analysis of Static Experimental Results

3.1. Analysis of Mass. The change of mass under the action of freeze-thaw cycles is one of the important indicators for the frost resistance property of concrete. By weighing the rubber concrete specimens after applying different numbers of freeze-thaw cycles, the mass loss rate of rubber concrete was obtained. As mentioned earlier, the number of freeze-thaw cycles was determined to be 0, 50, 100, and 150 in this study, and the corresponding mass loss rate is equal to 0%, 0.45%, 0.76%, and 1.30%, respectively, as shown in Figure 3. Compared to the mass loss of ordinary concrete under the same freeze-thaw cyclic conditions as reported in the
According to the qualitative relationship between the number of freeze-thaw cycles and the mass loss rate, it was proposed that the number of freeze-thaw cycles ($D$) had a linear deformation relationship with the mass loss rate ($M$). Correspondingly, the relationship equation as shown in Figure 2 and equation (1) was obtained based on the experimental data in this paper.

\[ M = 0.0083D. \]  

### 3.2. Analysis of Mechanical Parameters

The effect of the number of freeze-thaw cycles on the mechanical properties of rubber concrete was analyzed based on the loading strain rate of $10^{-5}/s$. The corresponding stress-strain curve is shown in Figure 4.

It can be seen from Figure 4 that, under the static loading strain rate, the compressive peak stress and elastic modulus of concrete are significantly decreased while the peak strain is gradually increased, as the number of freeze-thaw cycles increases. According to the overall trend under different loading conditions, all the stress-strain curves basically exhibit a consistent development trend, which can be divided into three stages: the elastic stage, the elastoplastic stage, and the decreasing stage. In the elastic stage, the stress grows linearly as the strain value increases, and the concrete satisfies Hooke’s law. The internal microdamage of concrete begins to expand as the load increases. When the concrete is unloaded to 0, part of the microdamage can be restored back to the state before loading. In the elastoplastic stage, the stress shows a nonlinear growth as the strain value increases. The internal damage and cracks of the concrete are in a stable expansion state. When the concrete is unloaded to 0, there will be a certain unrecoverable residual deformation value. In the decreasing stage, the stress begins to decrease gradually as the strain value increases. The internal cracks of
the concrete are in an unstable expansion stage. Even if the load no longer increases, the internal cracks will continue to develop and expand. According to the decreasing stage of the stress-strain curve, it can be seen that the plastic deformation ability of concrete is gradually strengthened as the number of freeze-thaw cycles increases.

From the compressive stress-strain curve under the static loading strain rate, as shown in Figure 4, the compressive peak stress of rubber concrete under different numbers of freeze-thaw cycles was extracted in order to examine the effect of the number of freeze-thaw cycles on the compressive peak stress of rubber concrete (Figure 5).

It can be seen from Figure 5 that, under the static loading strain rate, the compressive peak stress of rubber concrete is equal to 18.71 MPa when the number of freeze-thaw cycles is 0. As the number of freeze-thaw cycles increases, the compressive peak stress is gradually decreased. When the number of freeze-thaw cycles is increased to 150, the compressive peak stress becomes 11.07 MPa, suggesting a decrease of 40.86% relative to the condition without the freeze-thaw cycle. Compared to the compressive peak stress variation coefficient of ordinary concrete after freeze-thaw cycles as reported in the literature [24], the retention of compressive peak stress of the concrete containing 10% rubber is higher after freeze-thaw cycles, implying that the concrete with 10% rubber has a better frost resistance property. As a three-phase material, concrete contains a lot of microholes and microcracks after pouring and curing. When the liquid phase inside the concrete specimen begins to expand due to the decrease in temperature, the expanded volume that is higher than the coagulated volume of microholes and microcracks will generate an expansion pressure and exert tensile stress in a local area of the concrete. When the tensile stress is higher than the ultimate tensile stress of the cement slurry, a crack will occur. Eventually, as the number of freeze-thaw cycles increases, the compressive peak stress of concrete will be gradually decreased. In this paper, it is found that rubber concrete has a better frost resistance. This is mainly due to the fact that rubber materials have a property similar to the fixed air-entraining agent, which can effectively improve the frost resistance property of the concrete.

4. Analysis of Dynamic Experimental Results

4.1. Stress-Strain Curve. According to the dynamic compressive experiment plan under the action of different numbers of freeze-thaw cycles, the compressive stress-strain curves of rubber concrete under different loading conditions were obtained as shown in Figure 6.

According to Figure 6, the compressive stress-strain curves of rubber concrete under different loading strain rates share a similar development trend, which is basically consistent with Figure 3. It can be seen that, as the loading strain rate increases, the compressive peak stress and elastic modulus of concrete are gradually increased, while the peak strain shows a discrete trend. The specific changing trend of each parameter affected by the loading strain rate will be analyzed in detail later.

4.2. Characteristic Parameters

4.2.1. Peak Stress. Analysis of the effect of loading strain rate on the compressive peak stress of concrete is often based on the compressive peak stress dynamic increase factor (\( \alpha_{DIF-s} \)), as shown in the following equation:

\[
\alpha_{DIF-s} = \frac{\sigma_d}{\sigma_s}
\]  

where \( \sigma_d \) is the compressive peak stress of concrete under the dynamic loading strain rate; \( \sigma_s \) is the compressive peak stress of concrete under the static loading strain rate.

The effect of loading strain on the compressive peak stress of rubber concrete was examined and analyzed based on the compressive peak stress values extracted from the stress-strain curves under different numbers of freeze-thaw cycles (Figure 6). Then, the relationship between the strain rate and the compressive peak stress was obtained by using equation (1), as shown in Figures 7 and 8.

It can be seen from Figures 7 and 8 that the peak stress of rubber concrete under different numbers of freeze-thaw cycles is gradually increased as the loading strain rate increases. Specifically, when the number of freeze-thaw cycles is 0, the compressive peak stress of rubber concrete is equal to 18.71 MPa at the loading strain rate of \( 10^{-2} \) s\(^{-1} \). It is increased to 24.46 MPa at the loading strain rate of \( 10^{-2} \) s\(^{-1} \), suggesting an increase of 30.73% relative to the static loading condition. When the number of freeze-thaw cycles is 50, 100, and 150, the compressive peak stress of rubber concrete is equal to 16.64 MPa, 13.36 MPa, and 11.07 MPa, respectively, at the loading strain rate of \( 10^{-2} \) s\(^{-1} \) and is increased to 22.57 MPa, 19.04 MPa, and 16.47 MPa, respectively, at the loading strain rate of \( 10^{-2} \) s\(^{-1} \), suggesting an increase of 35.62%, 42.56%, and 48.80%, respectively, relative to the static loading condition. The literature [25] examined the compressive loading strain rate ranging from \( 10^{-3} \) s\(^{-1} \) to \( 10^{-2} \) s\(^{-1} \) and found that the peak stress of ordinary concrete was...
Figure 5: The effect of the number of freeze-thaw cycles on the peak stress of rubber concrete. (a) Peak stress. (b) Peak stress variation coefficient.

Figure 6: Continued.
generally increased by 30%~40%. Meanwhile, the effect of loading strain rate on the compressive peak stress of rubber concrete was slightly weaker than that of ordinary concrete. Such conclusions are consistent with the findings obtained by the literature [26-27] regarding the dynamic performance of rubber concrete with different substitution rates. According to the analysis above, it can be seen that the increasing amplitude of the compressive peak stress of rubber concrete affected by the loading strain rate is gradually enlarged as the number of freeze-thaw cycles increases. From the perspective of the mechanism of concrete strain rate effect, this is mainly because that concrete cannot form a uniform stress state under a high strain rate so that the evolution of concrete damage shows a retardation effect, which eventually leads to the phenomenon that the compressive peak stress is gradually increased as the loading strain rate increases. With the increase of the number of freeze-thaw cycles, the strain rate effect of rubber concrete is significantly intensified. The underlying mechanism lies in that, as the number of freeze-thaw cycles increases, the microcracks in the concrete gradually expand and begin to absorb water from the surrounding environment; due to the presence of moisture inside the concrete, the concrete...
adhesion effect will be gradually intensified with the increase of the strain rate, which eventually leads to the conclusions obtained in this study.

For the mathematical analysis of the effect of loading strain rate on the compressive peak stress of concrete, the expression form as shown in equation (3) is generally used when the loading strain rate is in a medium-low range (10^{-5}/s~10^{-3}/s) [13].

\[ \alpha_{\text{DIFF-}a} = b_1 + a_1 \log \left( \frac{\dot{\varepsilon}_d}{\varepsilon_s} \right), \]  

(3)

where \( \dot{\varepsilon}_s \) is the compressive static loading strain rate; \( \dot{\varepsilon}_d \) is the compressive dynamic loading strain rate; \( a_1 \) and \( b_1 \) are undetermined parameters of the mathematical model.

Parameter \( b_1 \) is the compressive peak stress dynamic increase factor under the static strain rate, which is generally taken as 1. According to the dynamic compressive peak stress of rubber concrete under the action of different numbers of freeze-thaw cycles in this study, mathematical regression analysis was performed by applying equation (3), and the expression forms as shown in equations (4)–(7) and Figure 8 were obtained.

\[
\begin{align*}
\text{D-0} & \quad \alpha_{\text{DIFF-}a} = 1 + 0.08451 \log \left( \frac{\dot{\varepsilon}_d}{\varepsilon_s} \right), \quad (4) \\
\text{D-50} & \quad \alpha_{\text{DIFF-}a} = 1 + 0.09852 \log \left( \frac{\dot{\varepsilon}_d}{\varepsilon_s} \right), \quad (5) \\
\text{D-100} & \quad \alpha_{\text{DIFF-}a} = 1 + 0.12011 \log \left( \frac{\dot{\varepsilon}_d}{\varepsilon_s} \right), \quad (6) \\
\text{D-150} & \quad \alpha_{\text{DIFF-}a} = 1 + 0.13952 \log \left( \frac{\dot{\varepsilon}_d}{\varepsilon_s} \right). \quad (7)
\end{align*}
\]

It can be seen from equations (4)–(7) and Figure 8 that the mathematical model of equation (3) can effectively describe the changing trend of the compressive peak stress of rubber concrete affected by the loading strain rate under the action of different numbers of freeze-thaw cycles. The mathematical meaning of parameter \( a_1 \) in equation (3) can be interpreted as the quantitative description of the effect of loading strain rate on the compressive stress of concrete. Parameter \( a_1 \) is gradually increased as the number of freeze-thaw cycles increases, suggesting a changing trend consistent with the finding of qualitative analysis. In order to propose the relationship between the compressive peak stress dynamic increase factor of rubber concrete and the loading strain rate under the action of freeze-thaw cycles, a linear relationship equation was established between parameter \( a_1 \) and the number of freeze-thaw cycles (\( D \)). Then, by performing mathematical regression analysis, the expression forms as shown in Figure 9 and equation (8) were obtained.

\[ a_1 = 0.08267 + 3.73 \times 10^{-4} \times D, \]  

(8)

In order to examine the coupling effect of freeze-thaw cycles and loading strain rate on the compressive peak stress dynamic increase factor of rubber concrete, equation (8) was substituted into equation (3). Parameter \( b_1 \) was taken a value of 1 according to its specific meaning. Thus, the following equation was obtained:

\[ \alpha_{\text{DIFF-}a} = 1 + (0.08267 + 3.73 \times 10^{-4} \times D) \times \log \left( \frac{\dot{\varepsilon}_d}{\varepsilon_s} \right). \]  

(9)

4.2.2. Elastic Modulus. Elastic modulus is one of the important parameters in the analysis of concrete mechanical properties. In general, the elastic modulus of concrete under different loading conditions can be calculated using the following equation based on the compressive stress-strain curve.

\[ E = \frac{\sigma_{0.5} - \sigma_{0.1}}{\varepsilon_{0.5} - \varepsilon_{0.1}}, \]  

(10)

where \( \sigma_{0.1} \) and \( \varepsilon_{0.1} \) refer to 10% of the compressive peak stress and peak strain of concrete, respectively; \( \sigma_{0.5} \) and \( \varepsilon_{0.5} \) refer to 50% of the compressive peak stress and peak strain of concrete, respectively.

Based on the compressive stress-strain curves of rubber concrete under the action of different numbers of freeze-thaw cycles and loading strain rates, equation (10) was applied to calculate the elastic modulus under different loading conditions. Then, following the same analysis method as for the compressive peak stress, the effect of loading strain rate on the elastic modulus of rubber concrete was analyzed as shown in Figures 10 and 11.

It can be seen from Figures 10 and 11, at the same number of freeze-thaw cycles, the elastic modulus of rubber concrete shows a gradually increasing trend as the loading strain rate increases. For the number of freeze-thaw cycles of 0, 50, 100, and 150, the corresponding elastic modulus under the static loading strain rate is equal to 8.85 \times 10^3 MPa, 6.67 \times 10^3 MPa, 4.16 \times 10^3 MPa, and 2.40 \times 10^3 MPa, respectively. When the loading strain rate is 5 \times 10^{-2}/s, the corresponding elastic modulus of rubber concrete is increased to 11.56 \times 10^3 MPa, 10.01 \times 10^3 MPa, 6.55 \times 10^3 MPa, and 3.96 \times 10^3 MPa, respectively. Thus, under the action of loading strain rate, the elastic modulus of rubber concrete is increased by 30.70%, 54.58%, 63.11%, and 68.03%, respectively. Based on the overall trend analysis, it can be seen that the elastic modulus of rubber concrete is gradually increased under the action of loading strain rate as the number of freeze-thaw cycles increases.

\[ a_{\text{DIFF-E}} = 1 + a_2 \log \left( \frac{\dot{\varepsilon}_d}{\varepsilon_s} \right). \]  

(11)

According to the dynamic elastic modulus of rubber concrete under different numbers of freeze-thaw cycles, equation (11) was applied to perform mathematical regression analysis, which derived the expression forms as shown in the following equations and Figure 11.
From Figure 11 and equations (12)–(15), it can be seen that equation (11) has good applicability for describing the effect of loading strain rate on the concrete elastic modulus dynamic increase factor $\alpha_{DIF-E}$ under different numbers of freeze-thaw cycles. By comparatively analyzing the undetermined parameter $a_2$ in equation (11), it is observed that the increasing amplitude of the elastic modulus is gradually enlarged under the action of loading strain rate as the number of freeze-thaw cycles increases. The quantitative analysis conclusions are therefore consistent with qualitative analysis.

4.2.3. Peak Strain. The peak strain values were extracted from the compressive stress-strain curves of rubber concrete under different loading conditions. The effect of loading strain rate on the peak strain of rubber concrete under different numbers of freeze-thaw cycles was analyzed based on the relative value of peak strain $\varepsilon_d/\varepsilon_s$, as shown in Figures 12 and 13.

It can be seen from Figures 12 and 13 that the peak strain of rubber concrete is gradually increased as the number of freeze-thaw cycles increases, and the loading strain rate has a minimal effect on this trend. When the number of freeze-thaw cycles is 0, 50, 100, and 150, the compressive peak strain of rubber concrete falls in the range of 2563 με–2836 με, 2716 με–3042 με, 3521 με–3895 με, and 4267 με–4657 με respectively, at a loading strain rate between $10^{-5}$/s and $5 \times 10^{-2}$/s. Affected by the loading strain rate, the changing amplitude of peak stress is 0%–10.65%, −10.19%–0.60%, −9.60%–0%, and −4.48%–4.25%, respectively. The analysis above implies that the loading strain rate has a discrete effect on the peak strain of rubber concrete. In the existing literature, the conclusions on the effect of loading strain rate on peak strain can be summarized as follows: (1) the peak strain is gradually increased as the loading strain rate increases; (2) the peak strain is gradually decreased as the loading strain increase; (3) there is no clear trend in the peak strain as the loading strain rate increases. The finding of this study is consistent with the third conclusion, which is mainly attributed to the coupling effect of the randomness, discreteness, and rate dependence of concrete materials [28].
5. Discussion

The split-tensile section of the rubber concrete with a 10% rubber replacement rate and the compressive failure mode of the rubber concrete under the static strain rate without going through freeze-thaw cycles is shown in Figure 14.

Compared with the split-tensile section and compressive failure mode of ordinary concrete, the failure section of rubber concrete appears to be relatively uneven and shows an obvious concave-convex failure mode. For the static compressive failure mode, the integrity of rubber concrete after compressive failure is higher than that of ordinary concrete, while the number of cracks, size, and brittleness characteristics of rubber concrete is all lower than that of ordinary concrete. The main reason for this is that the interface between the mortar and coarse aggregates is modified by the effect of rubber particles. To a certain extent, rubber particles inhibit the development of cracks and the rapid destruction of the specimen.

In the present study, the static and dynamic mechanical properties of rubber concrete with a 10% rubber replacement rate were examined under freeze-thaw cycles. The experimental results show that, compared with the freeze-thaw mechanical properties of ordinary concrete as reported in the literature, rubber particles exhibit a significant improvement effect on the mechanical properties of concrete under freeze-thaw cycles. The possible mechanism is that the rubber particles distributed in the concrete have strong deformability and provide a good buffer effect for the expansion of ice, which can inhibit the development and extension of cracks under freeze-thaw cycles to a certain extent. Meanwhile, rubber particles have a rough surface and can easily carry a part of the air component. Thus, they can exert a certain air-entraining effect, thereby improving the
antifreezing property of concrete. The existing literature [9, 29] has carried out research on the influence of rubber replacement rate on the antifreezing property of rubber concrete, and the results showed that the rubber concrete with a rubber replacement rate of about 10% had the best antifreezing property. Therefore, in this paper, the 10% rubber replacement rate was used to examine the compressive dynamic performance of rubber concrete.

The failure of concrete is mainly a kind of instability state driven by energy, which is directly related to the internal damage evolution of the material and the energy consumption of plastic friction. The higher the strain rate, the faster the initial damage develops, and the greater the fracture energy is required by the concrete. Thus, the concrete shows a significant strain rate effect. With the increase in the number of freeze-thaw cycles, the micro-cracks and pores of rubber concrete gradually develop and expand, and its deformability is gradually improved. As a result, the initial internal damage of rubber concrete gradually increases with the increase in the number of freeze-thaw cycles. Eventually, with the increase of strain rate, the internal damage evolution and energy consumption of rubber concrete under a large number of freeze-thaw cycles are relatively large, so that as the number of freeze-thaw cycles increases, the strain rate effect of rubber concrete shows a gradually increasing trend.

6. Conclusions

From the experimental study on the compressive dynamic performance of rubber concrete under the action of different numbers of freeze-thaw cycles and loading strain rates, the compressive stress-strain curves of rubber concrete were obtained. By analyzing the mechanical characteristic parameters of rubber concrete (i.e., peak stress, elastic modulus, and peak strain) under different loading conditions, the following conclusions were drawn.

(1) The development trend of the compressive stress-strain curve of rubber concrete is not affected by the number of freeze-thaw cycles and loading strain rate. As the number of freeze-thaw cycles increases, the plastic deformation ability of the compressive stress-strain curve is gradually strengthened. At the same loading strain rate, the compressive peak stress and elastic modulus of rubber concrete are gradually decreased while the peak strain is gradually increased as the number of freeze-thaw cycles increases. Compared to ordinary concrete, rubber concrete has a better frost resistance property.

(2) For the same number of freeze-thaw cycles, the compressive peak stress and elastic modulus of rubber concrete are gradually increased as the loading strain rate increases, while the effect of loading strain rate on the peak strain is relatively discrete. As the number of freeze-thaw cycles increases, the compressive peak stress and elastic modulus dynamic increase factors of rubber concrete are gradually increased under the action of loading strain rate.

(3) The compressive peak stress and elastic modulus dynamic increase factors of rubber concrete have a linear relationship with the dimensionless logarithm of the loading strain rate. Based on the coupling effect of freeze-thaw cycles and strain rate, a model equation for calculating the compressive peak stress dynamic increase factor was proposed. Meanwhile, the stress mechanism of rubber concrete under the coupling effect of freeze-thaw cycles and strain rate was discussed and analyzed.

Data Availability

The nature of the data is the experimental data of the compressive dynamic performance of rubber concrete under freeze-thaw cycles. The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Figure 14: 10% rubber concrete with 0 freeze-thaw cycles. (a) Specimen section. (b) Static compressive failure mode.
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