Research Article

Research on Dynamic Compressive Performance of Polypropylene Fiber-Reinforced High-Strength Concrete under Freeze-Thaw Environment

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1. Introduction

Concrete is considered to be one of the most important building materials. Practice has proved that it has excellent properties that other materials cannot replace [1, 2]. During the use of concrete buildings in cold regions, they are bound to be subjected to freeze-thaw cycle and dynamic loads [3]. The freeze-thaw effect of concrete will degrade the concrete, reduce the safety of the building structure, increase maintenance and reinforcement costs, and cause a lot of economic losses [4]. The use of polypropylene fiber-reinforced high-strength concrete (PFRHSC) can reduce the impact of freezing and thawing. High-strength concrete (HSC) has strong frost resistance. It can effectively resist the effects of freezing and thawing and improve the durability of concrete [5]. However, HSC has strong brittleness and plastic shrinkage, which is not conducive to its widespread use in construction projects. Adding polypropylene fiber (PPF) can effectively inhibit the development of cracks [6, 7]. Richardson et al. [8] found that PPF has good resistance to hydrostatic pressure, and a large amount of fiber evenly distributed in the concrete composite material can form a grid structure under the freeze-thaw cycle, which has a supporting effect on the aggregate. Zhang and Li [9] found that PPF fiber has a certain air entraining effect in concrete, which improves the air content of concrete to a certain extent, so as to improve the frost resistance of concrete. Among many kinds of fibers, PPF has been widely used in the industry because of its low price, enhanced cohesion of concrete mixture, long-distance pumping, freeze-thaw resistance, peeling resistance, and other advantages [10]. In addition, PPF has good mechanical properties [11], which enables polypropylene fiber-reinforced concrete (PFRC) to exhibit certain impact resistance performance when subjected to impact loads [12, 13]. So far, many scholars have studied the properties of PFRC. Chen et al. [14] used high
temperature and ultraviolet rays to deteriorate the PFRC specimen, and then used an improved wheel impact testing machine to conduct an impact test on the specimen and used CT equipment to perform internal imaging of the specimen. Studies have found that fibers can reduce the density and number of micro-cracks in the large pores of the concrete, making the overall denser. Zhang et al. [15] used split Hopkinson pressure bar (SHPB) to study the influence of different concrete water-cement ratios and PPF content on the dynamic mechanical properties of PFRC, and obtained a constitutive model of the specimen under dynamic compression. They also combined with the ZWT model to verify the correctness of the conclusion. Ren and Lai [16] studied the PFRC under freeze-thaw cycle and sulfate environment, combined with the hydrostatic pressure theory and osmotic pressure theory proposed by powers, studied the compressive strength, mass loss, and microstructure of the concrete test block, and obtained the PPF in the optimal content of concrete and its corresponding increase in strength; the theory of concrete failure in sulfate environment is put forward. In summary, the research mainly focuses on the pseudo-static and dynamic mechanical properties of PFRC at low strain rates or the dynamic performance of PFRC does not consider the effects of the freeze-thaw cycle, or the durability and the strength level of concrete are unsatisfactory, which is not conducive to the construction of large buildings in cold regions. Therefore, this test uses a large-diameter SHPB device to study the effects of different freeze-thaw cycles and different strain rates on the mechanical properties of PFRHSC under the premise that ordinary concrete cannot meet the increasing development of construction in cold regions and provide a scientific basis for further research on the durability and robustness of building structures in cold regions.

2. Materials and Methods

2.1. Material and Methods for Concrete. The concrete used in this test is C60 according to Chinese standards [17]. The cement used in the concrete is Qilianshan PII52.5 Portland cement, fine aggregate is natural river sand with a fineness modulus of 2.7, and coarse aggregate is 5 mm~10 mm crushed stone.

The concrete mix ratio is shown in Table 1. This mix ratio used in the test is the mass of materials required to produce one cubic meter of concrete.

Polypropylene fiber: This test uses Tuosheng brand polypropylene fiber with a length of 12 mm, and its parameters are shown in Table 2. Studies have shown that the mixing amount of chopped polypropylene fiber in concrete should be 0.9 kg/m³ [18].

According to Chinese standards [19], coarse aggregate, fine aggregate, polypropylene fiber, and cement are added to the horizontal shaft forced mixer for dry mixing for 60 seconds. After adding water, stir again for 240 seconds. The mixed concrete is put into the mold and vibrated to compact it. After 24 hours, the mold will be removed. Under the standard curing condition of 20 ± 2°C and 95% humidity, it will be cured for 28 days.

2.2. Specimen Design. The distribution of aggregates in concrete is not uniform, so the larger the size of SHPB specimen, the smaller the impact of uneven aggregates on the test. There are a large number of micro-cracks in the specimen. In order to reduce the impact of micro-cracks on the SHPB dynamic test, the size of the specimen needs to be limited [20]. Gray [21] proposed that the smallest length-to-diameter ratio of the SHPB specimens is $\sqrt{3v/4}$, where Poisson’s ratio $\nu = 0.33$. The size of the end face of the specimen should be as close as possible to the size of the bar to prevent the dispersion phenomenon [22]. Therefore, the diameter of the cylindrical specimen used in this test is 73 mm and the height is 37 mm.

ASTM C39 [23] requires that the angle between the normal direction of the end face of the test piece and the axial direction is less than 0.25°. In order to ensure the accuracy of the data obtained in the SHPB test, a grinder was used to smooth the surface of the cylindrical test block to prevent stress concentration on the uneven end surface and cause premature failure of the test piece.

According to China standards [24], the specimens that have been cured to a predetermined age are soaked in water for 4 days and placed in a rapid freeze-thaw test machine for 25 times, 50 times, 75 times, and 100 times freeze-thaw cycle. Every 25 times of freeze-thaw cycle, take out the test block, turn up and down, and put it into the freeze-thaw box to reduce the error caused by the temperature difference between the upper and lower parts of the specimen.

After freeze-thaw cycle for 100 times, the concrete on the surface of the specimen appeared spot-like peeling, which affected the flatness of the end surface. The surface of the SHPB test piece is treated with unsaturated polyester resin glue to prevent stress concentration caused by uneven end surface [25].

2.3. Principle of SHPB Test. In the SHPB test, both the incident bar and the transmission bar are regarded as linear elastic bars. At this time, the stress wave in the bar can be guaranteed to propagate in one dimension. This assumption is the assumption of one-dimensional stress wave. The stress waves generated in the test are all formed by the impact of incident bars and flat-headed bullets; see Figure 1. According to the assumption of one-dimensional stress waves, we can determine the elastic modulus of each bar is $E$ and the density of the bar is $\rho$. From this, the propagation velocity of the stress wave in the bar is calculated. The one-dimensional stress wave in the bar will propagate along the axis at a constant speed of $C_B = (E/\rho)^{0.5}$.

The average strain rate and strain calculation equation in the specimen are

$$\dot{\varepsilon} = \frac{C_B}{L_S} (t_f - t_R - t_I),$$

$$\varepsilon = \frac{C_B}{L_S} \int_0^T (\dot{t}_R - \dot{t}_I)dt.$$ (1)

The equation for calculating the stress on the two ends of the specimen from the elastic relationship is
\[ \sigma_1 = \frac{A_B}{A_S} A_B E (\varepsilon_I + \varepsilon_R), \]

\[ \sigma_2 = \frac{A_B}{A_S} \varepsilon_T. \]

\( A_B \) and \( A_S \) are the cross-sectional area of the bar and the test piece, respectively.

Assuming that the stress balance in the SHPB device satisfies the assumption of one-dimensional stress wave and the assumption of uniformity of the specimen, the specimen is approximately uniformly deformed, and the test results reflect the average material properties of the entire specimen. The stress can be expressed as

\[ \sigma_1 = \sigma_2, \]

\[ \varepsilon_I + \varepsilon_R = \varepsilon_T. \]

Simplify to get these equations

\[ \dot{\varepsilon} = -2 \frac{C_B}{L_S} \varepsilon_R, \]

\[ \varepsilon = -2 \frac{C_B}{L_S} \int_0^T \varepsilon_R dt, \]

\[ \sigma = \frac{A_B}{A_S} \varepsilon_T. \]

This method is called the “two-wave method,” which is obtained by simplifying the assumed conditions according to the calculation equation of the “three-wave method.” Therefore, the stress, strain, and strain rate of the specimen can be solved by using the two waveforms in the test. The “two-wave method” was used in this test.

2.4. Impact Loading. Place the damper of the transmission bar, connect the photoelectric speedometer, strain gauge, super-dynamic strain gauge, and oscilloscope, and ground it to reduce the interference of environmental noise to the instrument. Through the test without a specimen between the incident bar and the transmission bar, the average speed of the bullet is 6.75 m/s, 7.9 m/s, 8.9 m/s, and 11.4 m/s, respectively.

In order to reduce the influence of the three-dimensional stress caused by friction on the test results, a small amount of petroleum Vaseline was applied to both ends of the specimen [26], and the specimen was sandwiched between the SHPB incident bar and the transmission bar. After the check is correct, nitrogen is injected into the chamber, and the initial velocity of the projectile is controlled by the size of the air pressure. When gas is injected completely, check again whether the equipment is normal and whether the environment is safe. After confirming that it was normal, pressing the launch button, accompanied by a loud noise, the specimen was instantly destroyed into fragments. The placement of the test equipment is shown in Figures 2 and 3.

2.5. FFT-FIR Waveform Shaper. When using the SHPB test device, the dispersion phenomenon will have a greater impact on the test results of the SHPB device, so how to
reduce the interference of this phenomenon on the test is a problem that must be considered.

In 1971, Duffy et al. [27] proposed to install a pulse shaper on the SHTB device. The pulse shaping device uses the stress wave to perform multiple reflections, eliminates the high-frequency components generated by the bullet directly impacting the incident bar, and weakens the dispersion effect [28]. Frew et al. [29] applied the pulse shaping theory to the SHPB experiment and proposed and verified the theoretical model of the shaper. Common materials for pulse shaping devices are copper, aluminum, and even cardboard. Pang et al. [30] considered the impact speed and the density of the shaper, and improved the SHPB pulse shaping technology. The size and Young’s modulus of the physical pulse shaper affect the filtering effect of the incident wave. When the bullet speed is too fast, the shaper will fail [28].

In order to adjust the high-frequency components more flexibly, so that the waveform shaping is not affected by the impact speed, the size of the shaper, and the material, this test uses the incident bar end without a pulse shaping device. Use the “digital shaper” written by MATLAB to process the collected voltage signals to achieve the effect of pulse wave shaping. The frequency spectrum is an important feature of the signal, which reflects the frequency components and distribution of the signal. The frequency spectrum estimation of the signal is one of the important methods of signal analysis. The signal is difficult to detect in the domain in the global mode, but it is easy to distinguish when converted to the frequency domain. Therefore, the frequency spectrum is very effective in distinguishing the difference between periodic signals or non-periodic signals and periodic signals. This test uses FFT to analyze the frequency of the collected signal. The amplitude spectrum is drawn as shown in Figure 4.

The ordinate size reflects the signal energy at the corresponding frequency point; the higher the peak value, the higher the energy. It can be seen from Figure 4 that the frequency of the high-frequency component that causes the dispersion effect is above 30 kHz, and this component should be removed. Therefore, for the collected original signal, we hope to attenuate the frequency band that is higher and lower than the required frequency band, so the original signal is processed by the pass filter. The finite impulse response (FIR) filter can ensure the amplitude-frequency characteristics to ensure strict linear phase characteristics during signal processing [31]. The ripple of the passband and suppression band also needs to be considered, so the equal ripple method is used to design the FIR bandpass filter to process the signal. The signal before filtering is shown in Figure 5, and the processed signal is shown in Figure 6.

Studies have shown that the cost of using metal, rubber, and other pulse shapers to shape the waveform is the loss of a certain strain rate [20, 32]. This paper compares the stress-time after the digital shaper is not used and the digital shaper is used, as shown in Figure 7. It can be concluded that the fitting slope of the stress-time curve after reshaping has been reduced.

3. Results and Discussion

3.1. Stress-Strain Curve under Impact. Through the calculation of the data by the “two-wave method,” the stress-strain curves of the specimens with different freeze-thaw cycles under different strain rates are obtained, as shown in Figure 8.

The peak strength in the dynamic stress-strain curve reflects the ultimate strength of the concrete material.
under impact loads with different strain rates. It can be seen from Figure 8 that the peak strength of concrete under the same freezing and thawing times increases with the increase of strain rate. This phenomenon is consistent with the strain rate enhancement effect of concrete [33]. At the same time, as the impact velocity increases, the peak intensity gradually shifts to the right, and the peak strain increases.

Under the action of a relatively low strain rate, the stress-strain curve of the specimen under dynamic compression will decrease the peak strength of the stress-strain curve significantly as the number of freeze-thaw cycles increases; but when the strain rate is higher, with the increase of the number of freeze-thaw cycles, the peak intensity changes little. This phenomenon can be explained as the internal deterioration of the specimen is low, and the damage development is weak. When loaded with a higher strain rate, the effect of cracks on the strength of the specimen is less than that of the restraint on the strength of the concrete specimen under the action of triaxial forces. Under the same number of freeze-thaw cycles and different strain rates, the initial stress-strain curve is approximately straight and the slopes are similar. Later, the image changes to a convex curve, the slope of the curve with a small strain rate is small, and the slope of the curve with a large strain rate is larger.

In order to study the relationship between impact velocity, strain rate, and peak strength of the stress-strain curve, list Table 3 as follows:

In the test, when the impact velocity of the specimens from the FT0 group to the FT100 group is large (average velocity \( \geq 8.92 \text{ m/s} \)), there is almost no significant change in the peak strength. At a small impact velocity (average velocity \( \leq 7.92 \text{ m/s} \)), the peak strength of the specimen decreases significantly with the number of freeze-thaw cycles. At a larger impact velocity, the peak strength of the specimen is not greatly affected by freeze-thaw cycle.

It is found through experiments that the magnitude of the strain rate increases with increasing speed. Strain rate, as a condition for material testing, can be understood as an expression of loading speed. Concrete specimens with different freezing and thawing times were tested under SHPB devices with different impact speeds, and the corresponding strain rates at different impact speeds were obtained. At the same air pressure, the strain rates of the specimens with different freezing and thawing times did not change much. Velocities and strain rates were averaged separately for each loading condition, ignoring the effects of specimen composition. From the strain rate obtained from the similar impact velocity under different freezing and thawing times in the experiment, the relationship between velocity and strain rate can be plotted as shown in Figure 9, and the data are fitted to

\[
y = 25.35353x - 87.95378 \quad (R \quad \text{Square} = 0.97035) \tag{5}
\]

3.2. Dynamic Influence Factor. In order to explore the change of concrete compressive strength with strain rate under freeze-thaw action, the dynamic increase factor dynamic increase factor (DIF) is introduced here, which is one of the parameters
reflecting the dynamic performance of concrete materials. DIF is the ratio of the dynamic compressive strength to the static compressive strength of the concrete test block. However, the specific relationship between DIF and strain rate has not yet formed a unified relationship. Many scholars have given various equations for DIF and strain rate based on their own research.

Figure 8: Stress-strain curve of specimen under dynamic compression. (a) FT0. (b) FT25. (c) FT50. (d) FT75. (e) FT100.
Based on research, Tedesco et al. [34] concluded that DIF and $\lg(\varepsilon)$ are linearly related and gave the DIF SIGMAT:

$$\text{DIF} = 0.758\lg(\varepsilon) - 0.289 \quad \varepsilon \leq 63.1 \text{s}^{-1},$$

$$0.00965\lg(\varepsilon) + 1.058 \quad \varepsilon > 63.1 \text{s}^{-1}. \quad (6)$$

According to the research, Katayama et al. [35] obtained the relationship between DIF and $\lg(\varepsilon)$ as a quadratic function and gave

Table 3: Dynamic compression test results.

| Label | Times of freeze-thaw cycles | Velocity (m/s) | Strain rate (s$^{-1}$) | The peak intensity of stress-strain curve (MPa) |
|-------|-----------------------------|---------------|------------------------|-----------------------------------------------|
| FT0   | 0                           | 6.24          | 79                     | 69.31                                         |
| FT25  | 25                          | 6.26          | 78                     | 67.76                                         |
| FT50  | 50                          | 6.25          | 81                     | 65.78                                         |
| FT75  | 75                          | 6.26          | 77                     | 66.44                                         |
| FT100 | 100                         | 6.25          | 78                     | 64.65                                         |
| AVG   | —                           | 6.252         | 78.6                   | —                                             |
| FT0   | 0                           | 7.9           | 107                    | 77.56                                         |
| FT25  | 25                          | 7.9           | 109                    | 73.44                                         |
| FT50  | 50                          | 7.9           | 98                     | 73.62                                         |
| FT75  | 75                          | 8             | 105                    | 74.98                                         |
| FT100 | 100                         | 7.9           | 104                    | 73.12                                         |
| AVG   | —                           | 7.92          | 104.6                  | —                                             |
| FT0   | 0                           | 8.9           | 133                    | 85.42                                         |
| FT25  | 25                          | 8.9           | 131                    | 85.39                                         |
| FT50  | 50                          | 9             | 130                    | 84.27                                         |
| FT75  | 75                          | 8.9           | 139                    | 84.05                                         |
| FT100 | 100                         | 8.9           | 133                    | 86.07                                         |
| AVG   | —                           | 8.92          | 133.2                  | —                                             |
| FT0   | 0                           | 11.4          | 205                    | 99.81                                         |
| FT25  | 25                          | 11.4          | 201                    | 99.23                                         |
| FT50  | 50                          | 11.4          | 204                    | 102.11                                        |
| FT75  | 75                          | 11.5          | 213                    | 92.54                                         |
| FT100 | 100                         | 11.4          | 218                    | 98.39                                         |
| AVG   | —                           | 11.46         | 207.8                  | —                                             |

![Figure 9](image-url) Figure 9: The relationship between bullet speed and strain rate.

![Figure 10](image-url) Figure 10: Typical curves of different DIF models compared with test values.

Table 4: Coefficients in the fitting formula of DIF and $\lg(\varepsilon)$.

| Label | $a$     | $b$  | $c$   | $R$-square |
|-------|---------|------|-------|------------|
| FT0   | 0.37360 | -0.3774 | 0.48475 | 0.99       |
| FT25  | 0.30000 | 0.04823 | -0.07907 | 0.90       |
| FT50  | -0.00217 | 1.77965 | -2.09473 | 0.99       |
| FT75  | -0.74820 | 4.36210 | -4.23478 | 0.99       |
| FT100 | -0.88159 | 5.36096 | -5.66080 | 0.96       |
Figure 11: Relationship curve between DIF and \( \lg \varepsilon \). (a) FT0. (b) FT25. (c) FT50. (d) FT75. (e) FT100. (f) Second derivative value of DIF.
FIGURE 12: Parameters before and after the intermittent surface.

FIGURE 13: The relationship between $\lg \varepsilon$, DIF, and toughness. (a) FT0. (b) FT25. (c) FT50. (d) FT75. (e) FT100.
\[
\text{DIF} = 0.2583(\lg \dot{\varepsilon})^2 - 0.0508 \lg \dot{\varepsilon} + 1.021. \quad (7)
\]

Li and Meng [36] found that DIF has a linear function relationship with \(\lg \dot{\varepsilon}\) at low strain rates; at high strain rates, DIF has a quadratic function relationship with \(\lg \dot{\varepsilon}\) at low strain rates. See

\[
\text{DIF} = \begin{cases} 
0.034383 + \lg \dot{\varepsilon} + 1 \dot{\varepsilon} \leq 100s^{-1}, \\
1.73(\lg \dot{\varepsilon})^2 - 7.14\lg \dot{\varepsilon} + 8.53 \dot{\varepsilon} > 100s^{-1}.
\end{cases} \quad (8)
\]

Using the above three models, calculate the DIF with a strain rate of 75 s\(^{-1}\) to 250 s\(^{-1}\), and compare them with the experimental values as shown in Figure 10.

The “Test data” curve is close to the shape and growth trend of the Katayama model, but the DIF values calculated using the Katayama model are quite different, so a quadratic function equation similar to the Katayama model was chosen to fit the data. The fitting equation form is (9), where \(a, b, c\) are constants, and the values are shown in Table 4.

\[
\text{DIF} = a(\lg \dot{\varepsilon})^2 - b\lg \dot{\varepsilon} + c. \quad (9)
\]

As shown in Figure 11, the DIF value increases as \(\lg \dot{\varepsilon}\) increases. However, the time of freeze-thaw cycles makes the DIF and \(\lg \dot{\varepsilon}\) curve gradually flatten, and the second derivative of DIF gradually decreases with freeze-thaw cycles.

### 3.3. Toughness of Specimen

The toughness of the concrete specimen can be measured according to the stress-strain curve obtained from the SHPB test. Toughness reflects how much impact energy the specimen absorbs, and can reflect the fracture resistance of concrete when subjected to impact loads [37, 38]. The energy absorbed by each specimen can be quantitatively compared by calculating the area enclosed by the stress-strain curve and the x-axis according to equation [20].

\[
\omega = \int \sigma (\varepsilon) d\varepsilon. \quad (10)
\]

When the impact load is compressive stress, according to the conservation relationship between mass and energy, we can obtain the energy conservation equation on the intermittent surface, namely, the Rankine–Hugoniot equation; see

\[
(\sigma_1 v_1 - \sigma_0 v_0)Adt = 0.5\rho_0 A dX v^2_1 - v^2_0 + A\rho_1 dX (e_1 - e_0). \quad (11)
\]

In (11), \(\sigma\) means stress, \(v\) means velocity of mass point, \(\rho\) means density of the bar, \(A\) is the cross-sectional area of the bar, \(dX\) is the unit area in the direction of wave propagation, and \(e\) means the internal energy per unit mass; see Figure 12.

Equation (11) reflects the work done by external forces within \(dX\) unit length and \(dt\) time. \(A\rho_1 dX (e_1 - e_0)\) can be regarded as a constant, so it can be concluded that the external work on the intermittent surface has a quadratic relationship with the velocity. From the relationship between the impact velocity and the strain rate in Figure 9, we can conclude that the toughness of the specimen has a quadratic function relationship with \(\lg \dot{\varepsilon}\). Both DIF and toughness are related to \(\lg \dot{\varepsilon}\). The three-dimensional images of DIF, toughness, and \(\lg \dot{\varepsilon}\) are drawn, as shown in Figure 13, where the x-axis is \(\lg \dot{\varepsilon}\), the y-axis is DIF, and the z-axis is toughness.

With the increase of the number of freeze-thaw cycles, when the impact velocity is less than or equal to 7.92 m/s, the DIF and toughness show a decreasing trend. When the impact velocity is more than or equal to 8.92 m/s, the change of DIF and toughness is not obvious. When the times of freeze-thaw cycles are the same, under different impact speeds, DIF and toughness increase with the increase of loading speed. With the increase of impact speed, the faster the growth of DIF and toughness, the faster the energy absorbed by the specimen.

### 4. Conclusions

In this paper, through the dynamic compression test of PFRHSC specimens under different freeze-thaw cycles, the incident wave is processed by the FFT-FIR filter, and the stress-strain curve of the specimen under dynamic compression is calculated and drawn by the “two-wave method.” In this paper, the relationship among the average strain rate, compressive peak strength, DIF, and energy absorption density of the specimen is obtained through analysis, and it can be obtained.

1. The slope of the stress-time curve after FFT-FIR digital pulse shaping is reduced. Therefore, the digital shaping method is the same as metal, rubber, and other shaping devices at the expense of a certain strain rate. The pros and cons should be weighed when using it.
2. In the case of the same times of freeze-thaw cycles, the value of DIF increases as \(\lg \dot{\varepsilon}\) increases. As the times of freeze-thaw cycles increase, the trend of DIF increasing with \(\lg \dot{\varepsilon}\) will gradually slow down.
3. Under the action of a lower strain rate, the toughness tends to decrease as the number of freeze-thaw cycles increases. When the loading strain rate is high, the change is not obvious with the increase of freeze-thaw cycles. This phenomenon is consistent with the results of the stress-strain curve of the dynamic compression obtained in the experiment, reflecting the weaker internal deterioration of the concrete. DIF increases with the increase of toughness, reflecting that the impact energy absorbed by the specimen increases with the increase of strain rate, so DIF increases accordingly.

### Data Availability

All experimental data, models, and code generated or used during the study are available from the corresponding author by request.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.
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