Research Article

Experimental Study on the Effect of Freeze-Thaw Cycles on Axial Tension and Compression Performance of Concrete after Complete Carbonization

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The effect of freeze-thaw cycles on the axial tension and axial compression properties of completely carbonized concrete are investigated in this study. Three grade concrete specimens (C30, C40, and C45) were fabricated. The freeze-thaw cycle test was carried out on the completely carbonized specimens, followed by axial tension and axial compression tests. The results show that completed carbonization increases the axial tensile peak stress of C30, C40, and C45 concrete specimens by 8.7%, 9.7%, and 12.1%, respectively. The peak axial tension strain increased by 1.9%, 7.2%, and 9.6%, respectively. The peak axial compressive stress increased by 10.5%, 19.1%, and 24.1%, respectively. The peak axial compressive strain decreased by 13.7%, 14.1%, and 14.3%, respectively. With the increase of freeze-thaw cycles, the peak stress of tensile stress, peak strain, and compressive stress of concrete decrease continuously. The peak strain of compressive strain increases. The lower the strength grade of concrete, the faster the decline rate of stress and strain. According to the data changes of peak stress and peak strain at different times of freeze-thaw after carbonization, the stress-strain curve fitting formula for concrete under freeze-thaw cycles after complete carbonization is put forward, which has a good coincidence with the experimental result.

1. Introduction

Concrete structures exposed to the atmosphere are subjected to carbonization all year-round. Carbonization causes corrosion of steel bars and ultimately leads to insufficient durability of concrete structures [1, 2]. In winter and spring, concrete structures will also suffer from freezing-thawing (F-T) damage, which has become one of the main risk factors affecting concrete health and longevity, especially in higher latitudes areas [3, 4]. The repeated F-T cycles are responsible for continuous and disruptive internal pressure, which causes microcracking in the concrete and results in scaling and spalling [5, 6]. In recent years, the researches on concrete F-T cycles can be divided into three aspects. First, a large number of scholars have studied the mechanical performance of advanced concrete materials under freezing-thawing cycles. Li [7] studied the mechanical properties and F-T durability of basalt fiber reactive powder concrete. The result shows that steel fiber reactive powder concrete was more sensitive to the chloride salts when compared with that of the basalt fiber counterpart. Zhao [8] studied freeze-thaw resistance of class F fly ash-based geopolymer concrete. The freeze-thaw resistance was evaluated by mass loss, relative dynamic elasticity modulus, and compressive strength loss. Second, some scholars focus on the unique behavior of concrete materials under the action of the F-T cycles, such as fracture behavior [9] and bond behavior [10]. Finally, the mechanical properties of concrete under the simultaneous effects of F-T cycles and other actions are studied. For example, Xiao and Gou [11] summarized different conditions that can affect the carbonization performance of concrete; one common condition is the coexistence of freeze-thaw and carbonization. At present, researches on concrete properties after the combined action of carbonization and freeze-thaw cycles...
mainly focus on the mass loss rate, relative dynamic elastic modulus, compressive strength, flexural strength, tensile strength, carbonization depth, and carbonization area of concrete. Through freeze-thaw and carbonation cycle tests, Zhang et al. [12] discussed the change characteristics of carbonation depth and relative dynamic elastic modulus of fly ash fine aggregate concrete under the alternating action of freeze-thaw cycles and carbonation. Xiang et al. [13] designed cement-fly ash mortar and adopted the orthogonal design method, mainly studying the influence of carbonation on the compressive strength and antifreeze strength of the cube under freeze-thaw conditions. Mao et al. [14] revealed the deterioration mechanism of alternating freeze-thaw and carbonization through scanning electron microscopy (SEM) and X-ray diffraction (XRD). The results show that carbonization is beneficial to refine pore structure and improve concrete strength and delay freeze-thaw cycle damage during the initial alternate cycle.

The concrete stress-strain curve is of great significance to the mechanical performance of reinforced concrete structures. For example, the concrete material constitutive model can reflect the mechanical properties of concrete, including the ultimate strength of concrete. The stress-strain curve is the foundation of nonlinear structural analysis [15, 16].

Many scholars have conducted significant experimental research on the stress-strain curve of concrete which suffered freeze-thaw cycles. Shang et al. [17] carried out an experimental research on bidirectional tensile and compressive strength and deformation of common concrete after freeze-thaw cycle, tested tensile strength, stress-strain curve, and failure mode and analyzed the effects of freeze-thaw cycle times and stress ratio on tensile strength and corresponding tensile and compressive strains. Bai et al. [18] studied the complete stress-strain curves and deformation failure characteristics of recycled concrete through uniaxial compression tests of recycled concrete under different freeze-thaw cycles and revealed the influence of freeze-thaw cycles on the characteristic parameters of statistical damage constitutive model of recycled concrete. An and Jiaru [19] studied the complete stress-strain curve of stirrup confined concrete under different freeze-thaw cycles through axial compressive failure tests. Zhang [20] studied the mechanical properties of concrete after fatigue and freeze-thaw damage through the compression test of concrete under the interaction of fatigue load and freeze-thaw cycle.

It can be seen that there are not many studies on the mechanical properties of concrete under the combined action of carbonation and freeze-thaw cycles, and most of the studies focus on the effect of pure carbonation or pure freeze-thaw cycles on concrete performance [21–23]. However, in engineering practice, carbonization and freeze-thaw cycles exist simultaneously.

This paper studies the stress-strain curve equations of concrete under axial tension and axial compression after complete carbonization and freeze-thaw cycles tests, which provides experience for subsequent studies and provides an experimental and theoretical reference for the design of buildings in the cold region.

2. Materials and Methods

2.1. The Design of Specimens Tested. C30, C40, and C45 concrete specimens with the same external dimension of 100 mm × 100 mm × 400 mm were made according to the fast-freezing test system in Chinese Standard for Test Methods of Long-term Performance and Durability of Ordinary Concrete (GB/T 50082-2009) [24], and the pouring of the specimens is shown in Figure 1. After 28-day curing in the standard curing room, the average compressive strength of the concrete cube (f_{cu,k}) of the three specimens with strength grade C30, C40, and C45 is 30.4 MPa, 40.7 MPa, and 46.2 MPa, respectively. Then, a carbonization box was used to carbonize the specimens. After the test specimens were fully carbonized, they were taken out from the box and then dried at 60°C for 48 h, as shown in Figure 2. The dried specimens were placed in the carbonization box, and the distance between adjacent concrete test specimens should be greater than 50 mm, as shown in Figure 3. Then, the door of the carbonization tank was closed to ensure the CO₂ gas does not leak from the box. According to the research results of Gao and Zhang [25], it can be known that the increase of carbon dioxide concentration can accelerate the carbonization of concrete. Therefore, the CO₂ concentration in the carbonization box is controlled at about 30%, the relative humidity is within 65%∼75%, and the temperature is within 18°C∼22°C. Then, the three specimens were put into a carbonization box with other specimens to carbonize together, and all the specimens were not sealed with paraffin to accelerate carbonization. According to the standard, these three specimens were taken out every once in a while and broken at half the height of the specimens, and then, 1% concentration of phenolphthalain alcohol solution was used for titration after carbonization of the broken concrete specimen (Figure 4). If it is found that the broken specimen is not completely carbonized. It will continue to be carbonized in the carbonization box, and then after a longer time, it will be broken again at half the height of the specimen which has been broken. This is done repeatedly, until it is determined that the specimen has been completely carbonized. Under the same test conditions, one specimen is used to judge that complete carbonization is sufficient. Since the prismatic specimen is larger than the test specimen, as long as the cut prismatic specimen was completely carbonized, then the test specimens were also completely carbonized. The specimens were then placed in the freeze-thaw cycles box, as shown in Figure 5. Then, the uniaxial tension and compression tests were carried out to investigate the influence of freeze-thaw cycles on the characteristics of concrete properties and axial compression properties of the specimens after complete carbonization, and the corresponding numbers of freeze-thaw cycles after complete carbonization were 25, 50, 75, and 100 times. The mix proportion of the three strength grades of concrete used in this test is shown in Table 1.

In order to save material and cost, wood molds were used during the concrete injection. The size of the wood molds is shown in Figure 6. In order to ensure that the damage occurred in the middle part of specimen, the section in the
middle part of the specimen was reduced. To facilitate the test, four bolts with a length of 100 mm were embedded at both ends of the tensile specimen before casting. The embedded depth of bolts was 50 mm.

The external dimension of the axial compression member is 100 mm × 100 mm × 400 mm. Some researchers [26, 27] show that the smaller the ratio of the section length of prism specimen to the height of the specimen, the higher the axial compressive strength. When the ratio decreases from 1.0 to 0.5, the axial compressive strength of concrete increases rapidly. When the ratio decreases from 0.5 to 0.3, the change trend becomes smooth. When the ratio becomes smaller than 0.3, the change trend of compressive strength gradually tends to be stable. This is because the compressive strength is determined by the random distribution of the strength of the uniformly compressed part in the middle of the specimen. Within this range, the influence of the frictional resistance between the pressure plates and the test specimens can be eliminated [28], and the influence of the additional eccentricity caused by the longitudinal bending of the test specimens can be also eliminated.

In the test, a total of 108 nonstandard axial tension specimens and standard axial compression specimens of three strength grades (C30, C40, and C45) were poured, and the specific number and grouping are shown in Tables 2 and 3.

2.2. Axial Tensile Test Procedures. WDW-100 microcomputer controlled electronic universal testing machine was used in the axial tensile test, the maximum force is 100 kN, the accuracy level is 0.5 N, and the maximum tensile space is 600 mm. The TS3890 static resistance strain gauge was used to read the change of the displacement meter. The displacement meter used was YWD-50 displacement meter, and the testing accuracy is 0.01 mm. To ensure the measuring range of the displacement meter under its effective range, a specific fixing device was designed to set up the displacement meter. As shown in Figure 7, the fixing device is divided into upper and lower parts, made of aluminum alloy material, with two holes on each side to ensure the effective fixation between the fixing device and the specimen.

The steps of the axial tension test are as follows. (1) Fix the fixture and specimen with nuts. (2) Observe and adjust the position of the fixture so that the upper and lower...
tension pieces are in the same straight line. (3) Set up the fixing device, and adjust the measuring distance to 150 mm. (4) Install the displacement meter, and connect it to the static strain gauge. (5) Clamp the upper fixture; at this time, the specimen should still be clenched to prevent the specimen from sliding from the upper fixture. (6) Clamp the lower fixture after checking the horizontal and vertical direction of the specimen. (7) Prestretch before the test, stop when the test force is 1 kN, and check the change of the dial gauge reading on both sides. If the difference between the two sides of the data increases, adjust the position of the specimen and repeat this process until the change of the dial gauge reading on both sides is close. (8) Carry out formal loading. The loading mode of the testing machine was set as displacement loading, and the loading speed was controlled to be 0.05 mm/min. (9) Stop the test while the fracture of the specimen occurred. At the beginning of the test, the testing machine and the strain gauge began to collect data at the same time to ensure the one-to-one correspondence between load and displacement. The test site situation is shown in Figure 8.

2.3. Axial Compression Test Procedures. YAW-G3000 high stiffness rock concrete testing machine was used in this test, as shown in Figure 9. The maximum force is 3000 kN and the accuracy is 0.001 N. The type of data acquisition instrument used in this test was TDS-530 data acquisition instrument produced by Tokyo Testing Institute, Japan. As shown in Figure 10, YWD-50 displacement meter was used in this test. The accuracy is 0.01 mm. In order to avoid the damage to the displacement sensor caused by the debris falling in the process of concrete compression, the displacement sensor was wrapped with the sponge and electrical tape. In the
process of concrete compression test, the upper and lower ends of some specimen were destroyed due to excessive stress, resulting in the uneven stress state of the specimen. In order to avoid this situation, the upper and lower ends of specimen were wrapped with CFRP.

The steps of the axial compression test are as follows. (1) Connect the load signal of the high stiffness rock concrete testing machine and the displacement signal of the displacement sensor to the relevant channel of the static collector. (2) Grind the upper and lower surfaces of the specimen smoothly and place the specimen in the middle of the loading platform. (3) Set up displacement gauges on the surface of the specimen, and the displacement gauges should be placed vertically and their positions should be consistent. (4) Prepress the specimen, which can reduce the influence of uneven surface. (5) Observe whether the values of both displacement meters change the same before and after the prepressing. If the difference increases, adjust in time to avoid uneven stress of the specimen. (6) Carry out formal loading. Displacement loading was used in this test. The

| Strength grade | Specimen number | Number | Strength grade | Specimen number | Number | Strength grade | Specimen number | Number |
|---------------|----------------|--------|---------------|----------------|--------|---------------|----------------|--------|
| C30           | 30C0F0         | 3      | C40           | 40C0F0         | 3      | C45           | 45C0F0         | 3      |
|               | 30CF0          | 3      |               | 40CF0          | 3      |               | 45CF0          | 3      |
|               | 30CF25         | 3      |               | 40CF25         | 3      |               | 45CF25         | 3      |
|               | 30CF50         | 3      |               | 40CF50         | 3      |               | 45CF50         | 3      |
|               | 30CF75         | 3      |               | 40CF75         | 3      |               | 45CF75         | 3      |
|               | 30CF100        | 3      |               | 40CF100        | 3      |               | 45CF100        | 3      |

30C0F0 means that C30 concrete has no carbonation and freeze-thaw; 30CF50 means that C30 concrete is completely carbonized first, followed by freeze-thaw cycles of 50 times. Numbering of other specimens is similar.
initial loading speed was set at 0.3 mm/s. When the load reached 70% to 90% of the estimated peak load, the loading speed should be slowed down and adjusted to 0.1 mm/s. (7) Stop the test while the specimen is destroyed. The test site situation is shown in Figure 11.

3. Test Results and Discussion

In this section, the test phenomenon and stress-strain curves under tension and compression are discussed. Then, the tension and compression stress-strain constitutive models are fitted. The detail contents are as follows.

3.1. Failure Phenomenon of Specimens. After the specimens have been subjected to freeze-thaw cycles, the surface of different specimens presented different changes. When the number of freeze-thaw cycles was small, the appearance of C30 concrete specimens did not change significantly; basically no cement paste fell off and the degree of damage was light. With the increase in freeze-thaw cycles, a little cement paste fell off from the surface of specimens and slight cracks appeared. When the number of freeze-thaw cycles was large, the cement layer on the surface of concrete flaked obviously, the aggregate gradually exposed, and the local edges and corners of the specimen fell off, as shown in Figure 12. When the freeze-thaw cycle was 100 times, the end of the specimen was split when it was taken out of the specimen box. However, under the same freeze-thaw condition, the damage degree of C40 and C45 concrete was lighter than that of C30, as shown in Figure 13.

As shown in Figure 14, the fracture locations of the specimens occur in different parts. Most of the damage locations are the half of the specimens, which belong to the ideal damage locations. However, a small part of the damage locations is located at the changing section of the specimen, but all the damage locations are located within the 150 mm measuring region which can be measured by displacement gauges.

When the test specimen ruptured, only one main crack perpendicular to the loading direction was generated, illustrating that stress concentration did not occur and the specimen was destroyed by a unidirectional stress state. As shown in Figure 15, most of the fracture surfaces are perpendicular to the length direction of the specimens, and the fracture surface is uneven. The majority of the area in the fracture surface is a bond failure between coarse aggregate and cement mortar.

The compressive failure process of concrete is that the internal microcracks of the specimens occurred and expanded continuously during loading and finally broke down. At the beginning of loading, the stress of concrete specimens was small ($\sigma < 0.4 f_c$), and the stress and strain increased proportionally. When the stress reached $0.8 f_c \sim 0.9 f_c$, the tearing sound from the cracks inside the concrete specimen could be heard faintly, but there were no visible cracks on the surface. When the load reached the ultimate load, the stress reached the ultimate stress. When the strain still increased, the bearing capacity showed a downward trend, and cracks appeared on the surface of the specimen. When the stress decreased to $0.7 f_c \sim 0.8 f_c$, the crack width in concrete developed continuously, the splitting sound became louder, and the strain was still increasing. When the stress decreased to $0.5 f_c \sim 0.6 f_c$, the short longitudinal cracks appeared successively on the surface of the specimen, and the cracks were discontinuous with each other. At this time, the bearing capacity decreased rapidly. When the stress decreased again, the main short cracks finally became diagonal cracks, and the width of cracks became wider. Finally, the cracks penetrated the whole section, and the cracks in other parts did not develop anymore.

The failure phenomena of specimens under different freeze-thaw cycles were generally similar. As shown in Figure 16, the angle between the main diagonal crack and the horizontal direction is $58^\circ \sim 64^\circ$, which is the same as the test results of previous papers [29]. There was no damage to the ends of the specimen since the upper and lower ends of the specimens were wrapped with carbon fibers. It can be seen that the failure surface basically occurred at the interface between cement mortar and aggregate, and the coarse aggregate was rarely destroyed.

3.2. Peak Tensile Stress and Strain. The curves of peak tensile stress $f_t$ of three strength grades of concrete under axial tension are shown in Figure 17. The peak tensile strain $\varepsilon_t$ of concrete of three strength grades of concrete under axial tension is shown in Figure 18. The influence of carbonation
and freeze-thaw cycles after complete carbonation on the peak tensile stress and strain are analyzed as follows.

It can be observed from Figure 17 that when the concrete is completely carbonized, its axial tensile peak stress increases. The peak stress of C30 concrete increases by 8.7%, that of C40 concrete by 9.7%, and that of C45 concrete by 12.1%. That is to say, the higher the concrete grade, the greater the improvement of concrete tensile strength by carbonization. Another finding is that when the strength grade of concrete is high and the number of freeze-thaw cycles is low, the strengthening effect of carbonization is greater than the weakening effect of freeze-thaw cycles. For example, the concrete of C45 is frozen and thawed 25 times after full carbonization, and its peak stress is still greater than that of nonfrozen and noncarbonized concrete, which increases by about 5.3%, while the concrete of C30 and C40 have no such change. However, as the number of freeze-thaw cycles increases, the peak tensile stress decreases continuously. The lower the strength grade of concrete is, the earlier the tensile failure occurs.

According to Figure 18, it can be observed that the peak axial tension strain of concrete increases after complete carbonization; to be specific, complete carbonization increases the axial tensile peak stress of C30, C40, and C45 concrete specimens by 1.9%, 7.2%, and 9.6%, respectively. Since CaCO3 generated by carbonization fills the internal pore of concrete, and with the strength degree of concrete improves, the enhancement of carbonization is more obvious. Further, when the number of freeze-thaw cycles is low, the effect of carbonization still plays a dominant role, which is the same as previously mentioned, for example, the peak strain of specimens of C40 and C45, which under 25 times freeze-thaw cycles is slightly larger than that under nonfrozen and noncarbonized. Finally, improving the strength grade of concrete can effectively reduce the influence of freeze-thaw cycles. By comparing strain data between C45 and C40 specimens subjected to 100 times freeze-thaw cycles, the peak strain of C45 concrete decreased by 30.8%, while the peak strain of C40 concrete decreased by 35.3%.

3.3. Peak Compressive Stress and Strain. The peak compressive stress of three strength classes of concrete under axial compression is shown in Figure 19. It can be seen from Figure 19 that compared with the concrete without carbonation and freeze-thaw cycles, the peak compressive stress of each grade of concrete increases after complete carbonation, and the carbonation products increase the bearing capacity of concrete. For example, carbonization increases the peak compressive stress of C30, C40, and C45 concrete specimens by 10.5%, 19.1%, and 24.1%, respectively. However, after complete carbonation, the peak compressive stress decreases with the increase of freeze-thaw cycles.

The peak compressive strain of three strength grades of concrete under axial compression is shown in Figure 20. It can be observed that the peak compressive strain of all grades of concrete decreases after complete carbonization, indicating that carbonization will lead to the increase of concrete brittleness. To be specific, carbonization decreases the peak compressive strain of C30, C40, and C45 concrete specimens by 13.7%, 14.1%, and 14.3%, respectively. Further, the lower the concrete strength grade is, the faster the peak strain changes when the maximum failure load is reached. For example, when the number of freeze-thaw cycles increased from 50 to 75, the curve gradient of C30 specimen is greater than that of C40 specimen.

3.4. Axial Tensile Constitutive Model. The tensile stress-strain curves of concrete under different strength are shown in Figure 21.
Ordinary concrete is considered as a brittle material [30]. When the tensile stress of concrete is greater than the ultimate tensile stress, it will fracture. It can be seen from Figure 21 that the ideal curves of the rising section are obtained in the test, but when the axial tensile peak stress is reached, the curve decreases rapidly, and the measurement of the falling section is not ideal, which may be related to the test method and the testing machine itself. Therefore, this paper only analyzes the rising section of the stress-strain curve.

At the beginning of tension, the stress and strain increase in proportion at first, and then, the curve gradually tends to
level, and the maximum peak stress is reached. At this time, the bearing capacity of the specimen decreases sharply. The lower the concrete strength grade is, the easier the concrete is damaged.

Many researchers worldwide [31–34] have explored the axial tension constitutive relationship of concrete and summarized various forms of equations. Most scholars consider expressing the curve in the form of segments at the peak point. The commonly used rising segment curve equation forms are shown in Table 4.

The tensile stress-strain curves obtained obey the following geometric characteristics.

(a) When \( x = 0, y = 0 \), \( \frac{dy}{dx} = E_0 \), where \( E_0 \) is the ratio of tangent modulus of origin to secant modulus

(b) When \( x = 1, y = 1 \), \( \frac{dy}{dx} = 0 \)

(c) The slope of the ascending curve decreases monotonously and the curve is convex

When selecting the curve in this paper, the form of the curve should satisfy the previously mentioned conditions, and the form should be simple and convenient for derivation. Referring to the experience of the relevant literature [33], the sixth-degree polynomial is selected for fitting, and the specific form is as follows:
The curve parameter $a_1$ is fitted with the freeze-thaw times $N$ after complete carbonization, and the fitting form is as follows:

$$a_1 = p + qN + tN^2,$$

where $a_1$ is the parameter of the rising section of the curve; $N$ is the number of freeze-thaw cycles after complete carbonization; $p$, $q$, and $t$ are the regression coefficients.

The fitting results are as follows:

$$a_{1,30} = 1.102 - 0.0068N + 5.06 \times 10^{-5}N^2,$$

$$a_{1,40} = 1.129 - 0.00797N + 7.04 \times 10^{-5}N^2,$$

$$a_{1,45} = 1.139 - 0.00873N + 8.40 \times 10^{-5}N^2.$$

The relationship between the regression coefficients $p$, $q$, and $t$ and the mean value of cube compressive strength $f_{cu,m}$ are established as follows:

$$p = 0.0024f_{cu,m} + 1.03,$$

$$q = 1.20 \times 10^{-4}f_{cu,m} - 0.003,$$

$$t = 0.209f_{cu,m} - 1.34,$$

$$a_{1,CF} = (0.0024f_{cu,m} + 1.03) + (1.20 \times 10^{-4}f_{cu,m} - 0.003)N + (0.209f_{cu,m} - 1.34)N^2. \quad (7)$$

In the case of no carbonization and no freeze thaw, the curve parameters are fitted with the mean value of cube compressive strength $f_{cu,m}$ by a polynomial, and the following is obtained:

$$a_{1,COF0} = -0.0004f_{cu,m}^2 + 0.0301f_{cu,m} + 0.4812. \quad (8)$$

The comparison between the fitting curve and the measured curve of each strength concrete is shown in Figure 22, and $a_1$ is listed in Table 5.

It can be seen from Figure 22 and Table 5 that, within the range of freeze-thaw cycles in this test, the calculated fitting curve is in good agreement with the test results.

3.5. Axial Compressive Constitutive Model. The compressive stress-strain curves of concrete with different number of freeze-thaw cycles under each strength are shown in Figure 23.

With the change of test conditions, the changing trend of the stress-strain curve of concrete under axial compression is the same. The curve shows a concave trend in the rising section. This is because freeze-thaw makes the concrete lose internally and produces many tiny cracks. The higher the concrete grade, the worse the ductility and the more severe the curve decline. The stress-strain curve tends to be smooth before specimen fracture.

The stress-strain curve is the basis of nonlinear analysis by computers. First, the whole curve should be dimensionless, so that $x = \varepsilon/\varepsilon_{ot}$, $y = \sigma/f_{c}$. The stress-strain curve should satisfy the following geometric characteristics.

When $x = 0$, $y = 0$. 

When $x = 1, y = 1, \frac{dy}{dx} = 0$. When $x \to \infty, y \to \infty, \frac{dy}{dx} \to 0$. When $x \geq 0$, curve range is $0 \leq y \leq 1$.

At present, many scholars have put forward different fitting formulas for the stress-strain curve under axial compression, including exponential formula, rational fraction formula, trigonometric function formula, and polynomial formula. It can also fit the rising segment and the falling segment separately. The fitting method is simple and accepted by all. In this paper, with reference to the proposed curve of Guo of Tsinghua University [35], the ascending part of the stress-strain curve is fitted with cubic polynomial, and the descending part is fitted with rational formula. The formula is as follows:

$$y = \begin{cases} ax + (3 - 2a)x^2 + (a - 2)x^3, & x \leq 1, \\ \frac{x}{b(x-1)^2 + x}, & x \geq 1. \end{cases}$$

**Figure 21**: Tensile stress-strain curves under various test conditions. (a) C30. (b) C40. (c) C45.

**Table 4**: Formula of axial tension stress-strain curve equation.

| Curve segmentation | Form of equation |
|--------------------|-----------------|
| Rising section curve equation | $y = ax + bx^2 + cx^3$ [31] |
|                      | $y = a_0 + a_1x + a_2x^2 + a_3x^3$ [32] |
|                      | $y = a_0 + a_1x + a_2x^2 + a_3x^4$ [33] |
|                      | $y = ax/(bx^2 + 1)$ [32] |
|                      | $y = x/(ax^6 + y)$ [34] |
|                      | $y = 1.2x + 0.6x^6$ [32] |

$a, b, c, a_0, a_1, a_2, a_3, c, \beta, y$ are undetermined coefficients.
The parameter $a$ of the ascending section of the curve is fitted with the freeze-thaw number $N$ after carbonization. The fitting form is selected as follows:

$$a = p + qN,$$

(10)

where $a$ is the parameter of the rising section of the curve; $N$ is the number of freeze-thaw cycles after complete carbonization; $p$ and $q$ are regression coefficients.

The fitting results are as follows:

C30 fitting result $a = -0.02N + 1.62,$

(11)

C40 fitting result $a = -0.01N + 1.50,$

C45 fitting result $a = -0.009N + 1.29.$

(12)

The relationship between the regression coefficients $p$ and $q$ and the mean value of cube compressive strength $f_{cu,m}$ is established as follows:

$$p = -0.20f_{cu,m} + 2.24,$$

$$q = 7.31 \times 10^{-4} f_{cu,m} - 0.04,$$

$$a = (-0.20 f_{cu,m} + 2.24) + (7.31 \times 10^{-4} f_{cu,m} - 0.04) N.$$

(13)

The parameter $b$ of downward section of the curve is fitted with the freeze-thaw number $N$ after carbonization. The fitting form is selected as follows (11):

$$b = p + qN,$$

(14)
where \( b \) is the parameter of the downward section of the curve; \( N \) is the number of freeze-thaw cycles after complete carbonization; \( p \) and \( q \) are regression coefficients.

The parameter \( b \) of downward section of the curve is fitted with the freeze-thaw number \( N \) after carbonization, and the fitting result is as follows:

\[
\begin{align*}
\text{C30 fitting result } b & = 0.0102N + 2.23, \\
\text{C40 fitting result } b & = 0.0137N + 2.43, \\
\text{C45 fitting result } b & = 0.0069N + 2.94.
\end{align*}
\]

The relationship between the regression coefficients \( p \) and \( q \) and the mean value of cube compressive strength \( f_{cu,m} \) is established as follows:

\[
\begin{align*}
p & = 4.6 \times 10^{-2} f_{cu,m}^2 - 0.31 f_{cu,m} + 7.38, \\
q & = -10^{-5} f_{cu,m}^2 + 0.007 f_{cu,m} - 0.12, \\
b & = (4.6 \times 10^{-2} f_{cu,m}^2 - 0.31 f_{cu,m} + 7.38) \\
& \quad + (-10^{-5} f_{cu,m}^2 + 0.007 f_{cu,m} - 0.12)N. \quad (16)
\end{align*}
\]

### Table 5: Parameters of axial tension curve of concrete specimens of different grades.

| Strength grade of concrete | C0F0 | CF0 | CF25 | CF50 | CF75 | CF100 |
|---------------------------|------|-----|------|------|------|-------|
| C30                       | 1.0029 | 0.999 | 1.0939 | 0.988 | 1.3519 | 0.997 | 1.980 | 0.998 |
| C40                       | 1.0012 | 0.999 | 1.1651 | 0.999 | 1.0021 | 0.995 | 1.2015 | 0.984 | 1.3982 | 0.998 |
| C45                       | 0.9633 | 0.999 | 1.1449 | 0.999 | 0.9581 | 0.991 | 0.9206 | 0.992 | 0.9605 | 0.996 | 1.1026 | 0.999 |

*Note. \( R^2 \) is the fitting correlation coefficient. The closer to 1, the higher the fitting degree.*
Table 6: Parameters of uniaxial compression curve for prismatic specimens of different grades of concrete.

| Specimen number | $a$    | $R^2$  | $b$    | $R^2$  |
|-----------------|--------|--------|--------|--------|
| 30C0F0          | 1.4914 | 0.993  | 2.4407 | 0.983  |
| 30CF0           | 1.7456 | 0.995  | 2.2948 | 0.990  |
| 30CF25          | 1.0213 | 0.997  | 2.3781 | 0.990  |
| 30CF50          | 0.5041 | 0.996  | 2.7846 | 0.991  |
| 30CF75          | 0.3268 | 0.998  | 3.0145 | 0.978  |
| 40C0F0          | 1.4023 | 0.994  | 2.7942 | 0.990  |
| 40CF0           | 1.4578 | 0.987  | 2.3390 | 0.996  |
| 40CF25          | 1.3912 | 0.985  | 2.8913 | 0.979  |
| 40CF50          | 0.9338 | 0.995  | 3.1775 | 0.971  |
| 40CF75          | 0.7477 | 0.999  | 3.3714 | 0.991  |
| 40CF100         | 0.5912 | 0.999  | 3.8151 | 0.994  |
| 45C0F0          | 1.2335 | 0.995  | 3.1981 | 0.994  |
| 45CF0           | 1.4057 | 0.995  | 2.9525 | 0.995  |
| 45CF25          | 0.9786 | 0.953  | 3.0733 | 0.997  |
| 45CF50          | 0.7432 | 0.995  | 3.3228 | 0.989  |
| 45CF75          | 0.6015 | 0.995  | 3.4561 | 0.990  |
| 45CF100         | 0.4579 | 0.995  | 3.6177 | 0.998  |

Figure 24: Comparison of fitted curve and tested compressive stress-strain curve. (a) C30. (b) C40. (c) C45.
The comparison between the fitting curve and the measured curve of three kinds of concrete strength is shown in Figure 24.

The parameters $a$ and $b$ in the ascending and descending sections of the curve have definite geometric significance. When the value of $a$ is smaller and the value of $b$ is larger, the area under the curve is smaller, the curve shakes more, the material is brittle, and the failure process is faster. $a$ and $b$ are listed in Table 6.

As can be seen from Figure 24 and Table 6, within the range of the number of freeze-thaw cycles in this test, the fitting curves calculated are in good agreement with the test results.

4. Conclusions

The concrete specimens were completely carbonized and then were subjected to freeze-thaw cycles several times to study their axial tensile and axial compression properties, and the following conclusions were drawn.

(a) Carbonization makes the mechanical performance of concrete increase in bearing capacity but decrease in deformation capacity, and with the increase of concrete grade, the effect of carbonization on concrete is more obvious. To be specific, complete carbonization increases the axial tensile peak stress of C30, C40, and C45 concrete specimens by 8.7%, 9.7%, and 12.1%; the peak axial tension strain increased by 1.9%, 7.2%, and 9.6%; the peak stress of axial compression increased by 10.5%, 19.1%, and 24.1%; the peak axial compression strain decreased by 13.7%, 14.1%, and 14.3%.

(b) The freeze-thaw cycles are unfavorable to the mechanical performance of concrete. With the increase of the number of freeze-thaw cycles, the peak tensile stress, peak tensile strain, and peak compressive stress of concrete decrease. The strengthening effect of carbonization is greater than the weakening effect of freeze-thaw cycles when the strength degree of concrete is high. The ability to resist freeze-thaw cycles is enhanced with the improvement of concrete strength grade.

(c) Based on the measured tensile stress-strain curves, the ascending section of the axial tension stress-strain curve of concrete is fitted. The fitting curve agrees well with the test curve, and the parameters of the ascending section of the curve are analyzed. The relationship formula between curve parameter $a_1$ and freeze-thaw times and the average compressive strength of the cube is established. The section model is used to fit the rising and falling sections of the compressive stress-strain curve, respectively. The fitting curves are in good agreement with the test curves, and the curve parameters $a$ and $b$ are analyzed to establish the relationship between $a$ and $b$ and the number of freeze-thaw cycles after full carbonization and the average compressive strength of the cube. The fitting formula can be used in the finite element numerical simulation of concrete subjected to carbonization and freeze-thaw cycle.

Data Availability

The test data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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