Research Article

Life Prediction of Iron Ore Tailings Concrete under Freeze-Thaw Cycle Based on Weibull Distribution

Jie Han,1,2 Chun Fu,1,2 Songyang Liu,1,2 Haijun Li,1,2 Lunan Wang,1,2 Hai Sun,1,2 and Haotian Wu

1School of Civil Engineering, Liaoning Petrochemical University, Fushun 113001, China
2Liaoning Key Lab of Petro-chemical Special Building Materials, Fushun, China
3Xinyang Huaxin Investment Group Co. Ltd., Xinyang, China

Correspondence should be addressed to Jie Han; hanjie@lnpu.edu.cn

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Abstract

It is urgent to improve the comprehensive utilization rate of tailings, especially to solve the problem of fine iron ore tailings treatment and the shortage of natural sand. Therefore, a series of experimental research on iron ore tailings concrete under freezing-thawing cycles was carried out to analyze the attenuation law of the quality, compressive strength, and relative dynamic elastic modulus after different freezing-thawing cycles. The relative dynamic elastic modulus was used to define the damage factor, and the freezing-thawing damage model of iron ore tailings concrete was established based on Weibull distribution. The specific function form of two-parameter Weibull distribution of iron ore tailings concrete under freezing-thawing cycle was proposed, and the model was used to predict life of it. The results showed that, compared with the replacement rates of 20%, 60%, and 80%, the iron ore tailings with 40% replacement rate had the best improvement effect on the frost resistance of concrete and can delay the attenuation of the compressive strength of concrete. This model can not only predict the durability life of iron ore tailings concrete under freezing-thawing conditions, but also provide theoretical reference for the application of iron ore tailings concrete in cold areas.

1. Introduction

Iron ore tailings are one of the most widely distributed solid wastes in the world [1, 2]. Due to its low comprehensive utilization rate, a large amount of accumulation, serious environmental pollution, and resource waste are caused. Therefore, how to improve the comprehensive utilization rate of tailings has become an urgent worldwide problem to be solved [3, 4]. On the other hand, with the vigorous development of infrastructure, the consumption of concrete has increased year by year, resulting in a shortage of natural sand and price rises. Inevitably, iron ore tailings concrete is a win-win strategy from both an economic and an environmental protection point of view [1, 5–7]. Adding iron ore tailings into concrete not only improves the comprehensive utilization rate of iron ore tailings to some extent, but also solves the shortage of natural sand, thus fundamentally solving the problems of environmental pollution and sustainable development of resources.

Recently, some scholars have carried out a lot of research on the preparation and test of iron ore tailings concrete [4, 8–12]. Ling et al. [4] tried to use iron tailings as cementitious material to make ecofriendly ultrahigh performance concrete; their study found that the addition of iron tailings can improve the compactness of concrete, reduce CO₂ emissions, and improve the compressive strength of concrete. Tan et al. [13] studied the effective porosity, measured porosity, dry density, compressive strength, and permeability coefficient of pervious concrete using iron tailings as coarse aggregates; the results show that the
proportion design method based on target porosity is a more reasonable method for designing iron tailings-based pervious concrete. Zhang et al. [14] studied the concrete in which the river sand was replaced by the iron tailings of the same mass; the results show that the sieving curve and fineness modulus of iron tailing ore are similar to river sand, which can completely replace river sand in the production of concrete with similar workability and high mechanical strength and elasticity. Unfortunately, most of the researches are focused on the mechanical properties, but there are few reports on the frost resistance and freeze-thaw damage model of iron ore tailings concrete. It is well known that freeze-thaw damage is one of the important reasons for durability deterioration of concrete [15–17]. In freezing-thawing cycle, concrete often has the phenomenon of elastic modulus decline, strength attenuation, surface spalling, cracking, etc., which can cause buildings to break down or even collapse [18]. Hence, how to reduce the damage of concrete under freezing-thawing cycle and predict the durability of concrete structure during service is an urgent problem to be solved. It is an important premise for the application of iron ore tailings concrete in engineering practice to clarify the influence of iron ore tailings on the freeze-thaw resistance of concrete. In this paper, the influence of iron ore tailings on the rapid freeze-thaw is studied. Damage model of iron ore tailings concrete was established based on Weibull distribution [19, 20], and life prediction was also carried out, which provides a scientific theoretical basis for the extensive application of iron ore tailings concrete.

The aim of this paper is to investigate the freeze-thaw damage laws, damage model, and life prediction of iron ore tailings concrete. The rest of the paper is organized as follows. Section 2 introduces the freeze-thaw cycle experiment, which contains raw materials, mix proportion, and experimental method. Experimental results and discussion of freeze-thaw cycles test are performed in Section 3. Section 4 includes the freeze-thaw damage model and life prediction and the last part is conclusive remarks.

2. Materials and Methods

2.1. Raw Materials and Mix Proportion

2.1.1. Iron Ore Tailings. The iron ore tailings (Dandong Iron Mine, Liaoning, China) was employed to replace the natural sand, and the fineness modulus was 1.58. Chemical composition of selected iron ore tailings obtained through phase analysis is shown in Table 1.

2.1.2. Cement. The ordinary Portland cement P.O 32.5 produced from Fushun Cement Co., LTD, was adopted, and its chemical components and property indexes are shown in Table 2.

2.1.3. Coarse and Fine Aggregate. Natural pebbles and washed sand were selected in the experiment. The bulk density of pebbles is 710 kg/m³, and the apparent density is 2677 kg/m³. Natural washed sand was used in the experiment with fineness modulus of 2.84, apparent density of 2762 kg/m³, bulk density of 1478 kg/m³, crushing value of 10%, iron phase minerals of 5%–10%, and good particle size distribution.

2.1.4. Mix Proportion Design of Iron Ore Tailing Concrete. A kind of commonly used concrete C30 was designed for freezing-thawing cycles test and the proportion of iron tailing ore replacing natural sand was 0, 20, 40, 60, and 80%, respectively. Therefore, a total of 5 different combinations had been determined, as shown in Table 3. In order to study the effect of iron ore tailings replacing natural sand with different proportions on the mechanical properties of concrete, the water-binder ratio (W/B) of same grade concrete remains the same. Specific details are shown in Table 3.

2.2. Experimental Method. The rapid freezing-thawing method was adopted in the test according to the standard of the test method for long-term and endurance of ordinary concrete (GB/T 50082-2009) [21]. The freezing-thawing cycle time of the test was set within 2–4 h, the melting time was longer than 1/4 of the freezing-thawing time, the temperature during freezing was controlled at (-18 ± 2)°C, and the melting temperature was controlled at (5 ± 2)°C (Figure 1(b)). The maximum number of freeze-thaw cycles designed in this test was 120, and the test was conducted every 20 freezing-thawing cycles.

Two types of test specimen with different sizes were made, among which the cube specimen 10 cm × 10 cm × 10 cm was used to measure the axial compressive strength after freeze-thaw cycles, and the cuboid specimen 10 cm × 10 cm × 40 cm was used to measure the dynamic elastic modulus, as shown in Table 4.

The specific experimental steps were as follows:

(1) All specimens were maintained according to the standard curing method; then they were divided into two groups. Group A specimens with size of 100 mm × 100 mm × 100 mm were used for axial compression test and freeze-thaw test, and group B specimens with size of 100 mm × 100 mm × 400 mm were used for dynamic elastic modulus test, respectively.

(2) For the specimens participating in freezing-thawing experiment, after reaching the target number of freezing-thawing cycles, they were taken out for freezing-thaw testing, and the corresponding axial compressive strength and dynamic elastic modulus were obtained; the detailed tests are shown in Figure 1.

| Table 1: Chemical composition of iron ore tailings (%) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| SiO₂             | Fe₂O₃            | Al₂O₃           | CaO             | MgO             | K₂O             | CO₂             | Na₂O            | Ti₂O            |
| 54.4             | 9.26             | 5.65            | 3.78            | 2.98            | 1.37            | 1.2             | 0.87            | 0.43            |

\[ 2.30 \text{kg/m}^3 \]
Table 2: Technical performance of cement.

| Chemical composition (%) | Compressive strength (MPa) | Flexural strength (MPa) | Security | Specific surface (m²/Kg) | Setting time (min.) | Final setting (min.) |
|--------------------------|---------------------------|------------------------|----------|--------------------------|---------------------|---------------------|
| 3.7 5.6                  | 3 d 6 d                   | 3 d 6 d                | Conformity | 380                      | 120                 | 300                 |

Table 3: Mix proportion of iron ore tailings concrete (kg·m⁻³).

| Concrete | Replace rate (%) | Cement | Sand | Gravel | Iron ore tailings | Water | W/B |
|----------|------------------|--------|------|--------|-------------------|-------|-----|
| C30      | 0                | 470    | 654.05 | 1073.45 | 0               | 202.5 | 0.45 |
|          | 20               | 470    | 523.24 | 1073.45 | 130.81          | 202.5 | 0.45 |
|          | 40               | 470    | 392.43 | 1073.45 | 261.62          | 202.5 | 0.45 |
|          | 60               | 470    | 261.62 | 1073.45 | 392.43          | 202.5 | 0.45 |
|          | 80               | 470    | 130.81 | 1073.45 | 523.24          | 202.5 | 0.45 |

W/B: water-binder ratio, mass ratio of water to cementitious material.

Figure 1: Actual experimental pictures. (a) Freeze-thaw cycle test. (b) Temperature control curve of freeze-thaw. (c) Dynamic modulus test. (d) Uniaxial compression testing machine.
3. Experimental Results and Discussion

3.1. Mass Loss Analysis. Under freezing-thawing conditions, the internal damage of concrete accumulated gradually with the time of freezing damage, and its mechanical strength declined as a result. After several freezing-thawing cycles, denudation and degradation appeared on the surface of concrete (Figure 2).

From Figure 2, it can be found that the phenomenon of spalling was not obvious after 40 freeze-thaw tests, and a small amount of tiny holes can be seen on the surface of group A specimens. When the number of freezing-thawing cycles increased to 80, it can be seen that the surface of the specimens became rough, densely arranged small holes appeared, the amount of mortar falling off increases, and coarse aggregate was exposed. When the freezing-thawing

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**Table 4: The experimental plan and sample quantity of iron tailing concrete.**

| Concrete Replace rate (%) | Specimen size (mm × mm × mm) | Number of specimens | Experiment purpose                  |
|---------------------------|-------------------------------|---------------------|------------------------------------|
| 0                         |                               | 6 × 3               |                                    |
| 20                        |                               | 6 × 3               |                                    |
| 40                        | 100 × 100 × 100               | 6 × 3               | Freeze-thaw test and mechanical test |
| 60                        |                               | 6 × 3               |                                    |
| 80                        |                               | 6 × 3               |                                    |
| 0                         |                               | 3                   |                                    |
| 20                        |                               | 3                   |                                    |
| 40                        | 100 × 100 × 400               | 3                   | Relative dynamic elastic modulus test |
| 60                        |                               | 3                   |                                    |
| 80                        |                               | 3                   |                                    |

**Figure 2:** Damage pattern of concrete surface after freeze-thaw (number of freeze-thaw cycles: (a) 0 times; (b) 40 times; (c) 80 times; (d) 120 times).
cycles reached the extreme value of 120, the coarse aggregate exposure was spread almost all of the specimens, and the serious aggregates shedding resulted in significant honeycomb on the surface of the specimens. The calculation results and change trend of mass loss are shown in Table 5 and Figure 3.

The results in Figure 3 indicated that when the replace rate of iron ore tailings was 80%, the mass loss of specimens was the highest and reached 2.2%. The five experimental curves showed that the iron ore tailings concrete specimens mass increased in the early phase of the freezing-thawing test, since the water came into the microcracks of the specimens. However, as the number of freezing-thawing tests increased, mortar and aggregates fell off from the surface of specimens. Then, the weight of the specimens decreased, but their mass loss was less than 2.5% in all the tests. The results also showed that the mass loss of 40% iron ore tailings was lowest and further illustrated that its frost resistance was the best.

3.2. Analysis of Compressive Strength Loss. Compressive strength loss of concrete with different iron ore tailings replacement rates after freezing-thawing cycles is shown in

Table 6 and Figure 4. It can be seen from Figure 4 that residual strength of iron ore tailings concrete decreases gradually with the increase of freezing-thawing times, and the residual strength decreased faster after 60 freezing-thawing cycles. After 120 freezing-thawing cycles, the residual strength loss rate of 80% iron ore tailings concrete was the largest, the residual compressive strength was 21.6 MPa, and strength loss rate was 44.19%. Under the same conditions, the residual strength loss rate of 40% iron ore tailings concrete was the lowest, the residual compressive strength was 29.5 MPa, and strength loss rate was 30.76%. At the same time, the residual compressive strength of ordinary concrete without iron ore tailings was 26.2 MPa, and the strength loss rate was 34.83%, respectively.

The experimental results in Figure 4 showed that, compared with other replace rate, the replace rate of 40% iron ore tailings was best. It also can been found that, with the increase of freezing-thawing times, the loss rate of compressive strength of both ordinary concrete and iron tailing concrete increased gradually. Before 20 freezing-thawing times, the loss rate of compressive strength of ordinary concrete and iron tailings concrete was small, and there was

| Freeze-thaw cycles | 0% | 20% | 40% | 60% | 80% |
|-------------------|----|-----|-----|-----|-----|
| 0                 | 0  | 0   | 0   | 0   | 0   |
| 20                | -0.17 | -0.13 | -0.08 | -0.08 | -0.17 |
| 40                | 0.17 | 0.08 | -0.04 | 0.08 | 0.34 |
| 60                | 0.47 | 0.34 | 0.21 | 0.59 | 0.69 |
| 80                | 0.89 | 0.72 | 0.59 | 0.88 | 1.03 |
| 100               | 1.23 | 1.10 | 1.01 | 1.30 | 1.55 |
| 120               | 1.78 | 1.52 | 1.39 | 1.81 | 2.11 |

| Freeze-thaw cycles | 0% | 20% | 40% | 60% | 80% |
|-------------------|----|-----|-----|-----|-----|
| 0                 | 0  | 0   | 0   | 0   | 0   |
| 20                | 3.73 | 4.34 | 2.58 | 3.29 | 3.88 |
| 40                | 7.17 | 8.43 | 7.28 | 9.11 | 9.82 |
| 60                | 14.18 | 13.25 | 12.91 | 14.94 | 17.05 |
| 80                | 20.15 | 20.00 | 18.08 | 22.03 | 25.58 |
| 100               | 26.87 | 24.82 | 23.71 | 29.62 | 33.59 |
| 120               | 34.83 | 32.53 | 30.76 | 38.48 | 44.19 |
no significant difference between them. This was because the number of freezing-thawing times is less, and the damage caused by freezing-thawing was small. After 40 freezing-thawing times, with the increase of freezing-thawing times, the compressive strength loss rate of 20% iron tailing concrete and 40% iron tailing concrete was obviously lower than that of ordinary concrete. It showed that the addition of iron tailings improves the freezing resistance of concrete, mainly because the fineness modulus of iron tailings was smaller, which made the concrete structure more compact and reduced the formation of harmful holes in concrete.

3.3. Relative Dynamic Elastic Modulus. The dynamic elastic modulus of prismatic specimens (group B) with predetermined freezing-thawing times was tested according to the standard. Dynamic elastic modulus of iron ore tailings concrete after freeze-thaw was calculated by (1), and the relative dynamic elastic modulus can be calculated by (2). Relative dynamic elastic modulus of concrete with different iron ore tailings replace rates after freezing-thawing cycles is shown in Table 7 and Figure 5.

\[ E_n = 9.46 \times 10^{-4} Z L^3 f_n^2 / a^4 \times K, \]  

\[ P_n = f_n^2 / f_0^2 \times 100\%, \]  

where \( E_n \) means dynamic elastic modulus of concrete (MPa), \( a \) means the width of the specimen (\( a = 100 \) mm), \( L \) means the length of the specimen (\( L = 400 \) mm), \( Z \) means the mass of specimen (the actual measured mass), \( f_n \) means the measured transverse fundamental frequency (Hz), and \( K \) is the correction coefficient (in this paper, \( K = 1.4 \)).

where \( P_n \) means the relative dynamic elastic modulus after \( n \) freezing-thawing cycles and \( n \) is the number of freezing-thawing cycles, \( n = 0, 1, 2, \ldots, n \).

It can be seen from Figure 5 that the freezing-thawing cycles of iron ore tailings concrete were proportional to the relative dynamic elastic modulus. Among them, 40% iron ore tailings concrete had the smallest dynamic elastic modulus loss, and the corresponding thing was that 80% iron ore tailings concrete had the largest dynamic elastic modulus loss. During the freezing-thawing cycles 0-20, the relative dynamic elastic modulus changed slowly and the loss was small. This was mainly because the moisture absorbed inside the concrete was freezing-thawing at the microcracks, and the compactness of concrete was still maintained well, which inhibited the loss of the relative dynamic elastic modulus. After more than 20 freeze-thaw cycles, dynamic elastic modulus losses of 20% and 40% iron ore tailings concrete were both better than ordinary concrete without adding iron ore tailings. Obviously, when the replacement rate of iron ore tailings was 40%, the loss of relative dynamic elastic modulus was the least.

The pore size distribution of concrete with different iron tailings replacement rate could be identified by SEM observation in Figure 6. It can be seen that, with the increase of freezing-thawing cycles, the porosity of iron tailings concrete with different replacement rate gradually increased, the volume of individual pores gradually increased, and the connectivity between pores became easier. By comparing the pore characteristics of iron tailings concrete with different replacement rate in the same freezing-thawing cycles, it can be concluded that iron tailings can change the internal structure of concrete, and the improvement of the internal pore of concrete structure was most obvious when the replacement rate of iron tailings was 40%. This further proved that, among different replacement rates, 40% iron tailings replacement rate was the best for improving freezing-thawing and mechanical properties of concrete. Thus, attributing to the change of internal structure of iron tailings concrete, the loss of dynamic elastic modulus was well restrained. This also explained the minimum mass and strength loss of concrete with 40% iron tailings replacement rates.

4. Freeze-Thaw Damage Model and Life Prediction

The damage caused by freezing-thawing cycles weakened gradually from the surface to the interior of concrete and the

### Table 7: Relative dynamic elastic modulus (\( P_n \)) of C30 iron ore tailings concrete after freeze-thaw (%).

| Freeze-thaw cycles | Replace rate of iron ore tailings |
|--------------------|----------------------------------|
|                    | 0% | 20% | 40% | 60% | 80% |
| 0                  | 100| 100 | 100 | 100 | 100 |
| 20                 | 98.32 | 98.54 | 98.88 | 98.06 | 97.89 |
| 40                 | 96.12 | 96.77 | 97.00 | 95.70 | 95.21 |
| 60                 | 93.67 | 94.28 | 94.59 | 92.94 | 92.23 |
| 80                 | 90.82 | 91.18 | 91.85 | 89.84 | 88.91 |
| 100                | 87.72 | 88.17 | 88.93 | 86.83 | 85.46 |
| 120                | 84.27 | 84.99 | 85.84 | 83.64 | 81.84 |

![Figure 5: The relationship between the number of freeze-thaw cycles and relative dynamic elastic modulus.](image-url)
small changes in velocity of P-wave propagation. Therefore, it was reasonable to define freezing-thawing damage by dynamic elastic modulus \[22, 23\]. In this paper, the freezing-thawing damage model of iron ore tailings concrete was established based on Weibull distribution with the relative dynamic elastic modulus as damage variable, and the life prediction of iron ore tailings concrete under freezing-thawing environment in cold regions was carried out.

4.1. Freeze-Thaw Damage Analysis. There are many evaluation indexes for concrete damage so far, such as ultrasonic wave velocity (dynamic elastic modulus), length change rate, rebound value, erosion depth, and mass loss rate. A large number of degradation model studies had found that dynamic elastic modulus and strength loss rate were more suitable than mass loss rate as evaluation indexes of concrete loss \[22, 23\]. So in this paper, dynamic elastic modulus was selected as the damage evaluation index, and the freeze-thaw damage degree was defined based on damage mechanics and (3) as

\[
D(N) = \frac{E_0 - E(N)}{E_0} = 1 - P_n, \tag{3}
\]

where \(D\) means damage degree, \(E_0\) means initial dynamic elastic modulus of concrete (MPa), and \(E(N)\) means dynamic elastic modulus of concrete after \(N\) freeze-thaw cycles.

4.2. Damage Model of Iron Ore Tailings Concrete Based on Weibull Distribution. Recently, there are mainly two models to describe freezing-thawing damage of concrete \[19, 20\], namely, an exponential function as shown in (4) and a quadratic function as shown in (5). However, these two kinds of functions have some shortcomings: the exponential function and the quadratic function do not meet the boundary condition that the freezing-thawing damage rate of concrete was 0 when without freezing-thawing. The quadratic function relies on the statistical theory of test data, and we obtained the empirical formula based on the test. It is not rigorous enough to use this common formula to describe the random damage inside of concrete. In addition, in the phase of life prediction of concrete structure, the service life predicted by the deterministic model had certain fuzziness, so it is necessary to accurately predict the service life of concrete by using probability method.

\[
D(N) = 1 - ae^{bN}, \tag{4}
\]

where \(a, b\) mean material coefficients, respectively.

\[
D(N) = a_1N^2 + b_1N + c, \tag{5}
\]

where \(a_1, b_1, c\) mean material coefficients, respectively.

In 1939, Swedish scholar Weibull proposed a two-parameter Weibull distribution function for fatigue life data processing. Weibull distribution is a failure theory based on
chain model combined with statistics and probability theory. It is commonly used to reflect the probability distribution of material failure, and its life prediction function has been widely used in various fields, such as prediction of concrete damage and fatigue life [24–27]. Zhou et al. [28] studied the strength damage and life prediction model of pavement concrete under low-temperature loading and drying based on Weibull distribution, and the experimental results showed that the fatigue life of concrete under these conditions accords with Weibull distribution function, and the specific form of two-parameter Weibull distribution function of pavement cement concrete under low temperature drying load was proposed. So, when the fatigue failure of iron ore tailings concrete under freezing-thawing cycle follows Weibull distribution, the freezing-thawing damage degree and distribution function were equivalent as follows:

\[
D(N) = F(N) = \int f(N)\,dN = 1 - \exp\left[-(\frac{N}{\alpha})^\beta\right],
\]

where \(\alpha\) means characteristic fatigue parameter, \(\beta\) means shape parameter, \(\alpha > 0, \beta > 0\). \(f(N)\) is probability density function as follows:

\[
f(N) = \frac{\beta}{\alpha} \left(\frac{N}{\alpha}\right)^{\beta-1} \exp\left[-(\frac{N}{\alpha})^\beta\right],
\]

where \(f(N)\) is an index of density function (if \(\beta = 1\); \(f(N)\) can be regarded as a normal distribution density function (if \(\beta = 3 \sim 4\)).

4.3. Parameter Determination. Equation (6) is a non-polynomial function that cannot be fitted directly, so it is necessary to take twice logarithmic in order to get linearization, namely,

\[
\beta \ln N - \beta \ln \alpha = \ln \left(\ln \frac{1}{1-D}\right).
\]

It can be find that (6) is a linear form of \(Y = AX + B\) (namely, \(Y = \ln(\ln(1/1-D))\), \(X = \ln N\), and linear fitting and maximum likelihood estimation in mathematical statistics were used to obtain the values of characteristic parameters \(\alpha\) and \(\beta\). The correlation of characteristic parameters is shown in Figure 7. The estimation results of Weibull distribution function characteristic parameters of iron ore tailings concrete with different substitution rates are shown in Table 8. As can be seen from Table 8, the overall linear correlation coefficient is above 0.9967; it showed that the fatigue life of iron tailings under freeze-thaw cycle conforms to Weibull distribution.

The freeze-thaw damage degree calculated according to (7) is shown in Table 9, and the results were compared with the experimental values. The variance of the ratio between the test value and the calculated value was 0.0006, and the variation coefficient was 0.0244. It can be seen that the calculated values were in good agreement with the experimental values.

4.4. Damage Model. It was found from the above studies that the damage degree of iron tailings concrete was closely related to the freeze-thaw cycles and the replacement rate of iron tailings; it was supposed that the damage model should be able to reveal the influence of freezing-thawing cycles and iron tailings replacement rate on freezing-thawing damage of concrete at the same time. Therefore, two-dimensional damage model of single independent variable, as shown in (6), was no longer applicable. It is necessary to derive a new three-dimensional damage model containing two variables freeze-thaw cycles and the replacement rate of iron tailings.

The proposed three-dimensional multivariate freezing-thawing damage model can more effectively evaluate the freezing-thawing damage of materials in complex environment, and it was also more convenient to analyze the freezing-thawing evolution process of materials in complex environment. Some researchers had established three-dimensional freeze-thaw damage models of ordinary concrete and light aggregate concrete respectively according to the damage theory, but the model equation was relatively complex. In order to better serve engineering practice, in this paper, a new freezing-thawing damage equation \(D(n, m)\) with regard to the replace rate of iron ore tailings was proposed, by fitting \(\alpha\) and \(\beta\) in the freezing-thawing damage equation \(D(n) = 1 - \exp[-(n/\alpha)^\beta]\), as follows:

\[
\begin{align*}
\text{Replace rate ( %)} & \quad \alpha & \quad \beta & \quad B & \quad R^2 \\
0 & 487.9103 & 1.2849 & -7.9537 & 0.9989 \\
20 & 466.5424 & 1.3588 & -8.3503 & 0.9967 \\
40 & 435.0642 & 1.4584 & -8.8605 & 1.0000 \\
60 & 487.7295 & 1.2384 & -7.6654 & 0.9994 \\
80 & 444.4932 & 1.2462 & -7.5980 & 0.9996
\end{align*}
\]
\( D(n, m) = 1 - \exp \left( -\left( -\frac{n}{7143m^4 + 10540m^3 - 4448m^2 + 18.4m + 487.9} \right) \right), \) (9)

where \( n \) is the number of freeze-thaw cycles and \( m \) is the replacement rate of iron ore tailings.

4.5. Comparison and Discussion. In order to prove the accuracy of the proposed damage model, the experimental results were compared with the model fitting results of damage degree. According to Table 7 and (3), the damage degree based on relative dynamic elastic modulus and its fitting curve were calculated as shown in Figure 8(a). It showed the relationship between damage degree of iron ore tailings concrete with different replace rates and freeze-thaw cycles. It can be easily found from the figure that the damage degree difference between iron ore tailings concrete with different replace rates and ordinary concrete was small at the early stage of freezing-thawing cycle; after 40 freezing-thawing cycles, the freezing-thawing damage degree of 40% iron ore tailings concrete was significantly lower than others. It is further shown that 40% iron ore tailings replace rate was the optimal choice.

From Table 9, it can also be found that the freeze-thaw resistance of iron ore tailings concrete with 40% replace rate was significantly superior to other iron ore tailings concrete and ordinary concrete. When the freezing-thawing cycles was 60, the damage degree of 40% iron ore tailings concrete was 5.41%, and that of ordinary concrete and 20%, 60%, and 80% iron ore tailings concrete was 6.33%, 7.06%, and 7.77%, respectively. Meanwhile, the frost resistance of 40% iron ore tailings concrete was 0.92% and 2.36% higher than that of ordinary concrete and 80% iron ore tailings concrete, respectively. When the freezing-thawing cycles were 120, the frost resistance of 40% iron ore tailings was 1.57% higher than others.

### Table 9: The comparison between the calculated value and the experimental value of freeze-thaw damage degree.

| Replace rate (%) | Freeze-thaw cycles | E (%) | C (%) | E/C | E (%) | C (%) | E/C | E (%) | C (%) | E/C |
|-----------------|-------------------|-------|-------|-----|-------|-------|-----|-------|-------|-----|
|                 | 20                |       |       |     |       |       |     |       |       |     |
| 0               |                   | 1.68  | 1.64  | 1.02| 3.88  | 3.94  | 0.98| 6.33  | 6.54  | 0.97|
| 20              |                   | 1.46  | 1.38  | 1.06| 3.23  | 3.49  | 0.93| 5.72  | 5.98  | 0.96|
| 40              |                   | 1.12  | 1.11  | 1.01| 3.00  | 3.03  | 0.99| 5.41  | 5.41  | 1.00|
| 60              |                   | 1.94  | 1.90  | 1.02| 4.30  | 4.42  | 0.97| 7.06  | 7.19  | 0.98|
| 80              |                   | 2.11  | 2.08  | 1.01| 4.79  | 4.85  | 0.99| 7.77  | 7.91  | 0.98|
|                 | 40                |       |       |     |       |       |     |       |       |     |
| 0               |                   | 9.18  | 9.33  | 0.99| 12.28 | 12.23 | 1.00| 15.73 | 15.20 | 1.03|
| 20              |                   | 8.82  | 8.71  | 1.01| 11.83 | 11.60 | 1.02| 15.01 | 14.62 | 1.03|
| 40              |                   | 8.15  | 8.11  | 1.00| 11.07 | 11.05 | 1.00| 14.16 | 14.17 | 1.00|
| 60              |                   | 10.16 | 10.11 | 1.00| 13.17 | 13.11 | 1.00| 16.30 | 16.15 | 1.01|
| 80              |                   | 11.09 | 11.13 | 1.00| 14.54 | 14.43 | 1.01| 18.16 | 17.76 | 1.02|
|                 | 60                |       |       |     |       |       |     |       |       |     |
| 0               |                   | 9.01  | 9.23  | 0.99| 12.18 | 12.23 | 1.00| 15.73 | 15.20 | 1.03|
| 20              |                   | 8.69  | 8.71  | 1.01| 11.73 | 11.60 | 1.02| 14.91 | 14.62 | 1.03|
| 40              |                   | 8.15  | 8.11  | 1.00| 11.07 | 11.05 | 1.00| 14.16 | 14.17 | 1.00|
| 60              |                   | 10.16 | 10.11 | 1.00| 13.17 | 13.11 | 1.00| 16.30 | 16.15 | 1.01|
| 80              |                   | 11.09 | 11.13 | 1.00| 14.54 | 14.43 | 1.01| 18.16 | 17.76 | 1.02|

\( E \) means experimental value and \( C \) means calculation value.

**Figure 8:** Evolution of freeze-thaw damage with different replace rates. (a) Experimental value of damage degree. (b) Simulation value calculated by proposed damage model.
Table 10: Prediction of frost resistance and durability life of iron ore tailings concrete.

| Replace rate (%) | Northwest | North | Northeast |
|------------------|-----------|-------|-----------|
| 0                | 19.4      | 27.7  | 19.7      |
| 20               | 17.5      | 25.0  | 17.8      |
| 40               | 27.5      | 39.2  | 27.9      |
| 60               | 20.1      | 28.7  | 20.5      |
| 80               | 18.2      | 26.1  | 18.6      |

that of ordinary concrete 1.57% and 4.0% higher than that of 80% iron ore tailings. It indicated strongly that 40% iron ore tailings concrete can significantly improve the frost resistance of concrete without reducing the strength of concrete.

It can be concluded that different replacement rates and freezing-thawing damage evolution times in (8) were to establish a 3D freezing-thawing damage evolution diagram based on Weibull distribution characteristic parameters, as shown in Figure 8(b). Comparing Figure 8(a) (3D graph drawn according to the experimental results) with Figure 8(b), the damage degree was 0.4. The average numbers of freezing-thawing cycles per year were 120, 84, and 118 in the northwest, north, and northeast of China, respectively. Once indoor rapid freezing-thawing test was equivalent to 12 freezing-thawing cycles in natural environment, according to (9), the durability life of iron ore tailings concrete in northern of China was calculated. The results are shown in Table 10.

It can be seen from Table 8 that 40% replace rate iron ore tailings concrete had a longer service life than common concrete and other replace rates concrete. It was also concluded that the freezing-thawing resistance of common concrete was improved when mixed with iron ore tailings. The establishment of the damage model can not only predict the durability life of iron ore tailings concrete under freezing-thawing conditions, but also provide references for the popularization and application of iron ore tailings concrete in cold region.

5. Conclusions

(1) The relative dynamic elastic modulus of iron ore tailings concrete with 40% replace rate decreased gradually with the increase of freezing-thawing cycles, and the decline trend was slower than that of other iron ore tailings concrete and ordinary concrete without iron ore tailings. The addition of iron ore tailings can reduce the loss of dynamic elastic modulus and enhance the freezing resistance of concrete.

(2) With the increase of freeze-thaw cycles, the residual compressive strength of iron ore tailings concrete decreases continuously. And, after 120 freeze-thaw cycles, the compressive strength loss rate of iron ore tailings concrete with 40% replacement rate was 30.76%. Compared with other iron ore tailings concrete and ordinary concrete without iron ore tailings, the iron ore tailings concrete with 40% replace rate had the highest compressive strength and the best frost resistance.

(3) Based on experiments, it was verified that the fatigue life of iron ore tailings concrete under freezing-thawing cycles conforms to Weibull distribution, using the relative dynamic elastic modulus as the damage factor, a 3D freezing-thawing damage model was established with two independent variables of freezing-thawing cycles and tailings replacement rate. The specific function form of two-parameter Weibull distribution function of iron ore tailings concrete under freezing-thawing cycle was proposed in this paper. The establishment of the damage model can not only predict the durability life of iron ore tailings concrete under freeze-thaw conditions, but also provide reference for the popularization and application of iron ore tailings concrete in cold regions. However, this proposed function form was still too complex and tedious, which was not conducive to the practical application of engineering. We will continue to focus on the study of model simplification in the future.

Data Availability

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 regarding the publication of this paper.

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References

[1] S. Zhao, J. Fan, and W. Sun, “Utilization of iron ore tailings as fine aggregate in ultra-high performance concrete,” Construction and Building Materials, vol. 50, pp. 540–548, 2014.
[2] F. A. Kuranchie, S. K. Shukla, D. Habibi, and A. Mohyeddin, “Utilisation of iron ore tailings as aggregates in concrete,” *Cogent Engineering*, vol. 2, no. 1, Article ID 1083137, 2015.

[3] M. Gou, L. Zhou, and N. W. Y. Then, “Utilization of tailings in cement and concrete: a review,” *Science and Engineering of Composite Materials*, vol. 26, no. 1, pp. 449–464, 2019.

[4] G. Ling, Z. Shui, X. Gao, T. Sun, R. Yu, and X. Li, “Utilizing iron ore tailings as cementitious material for eco-friendly design of ultra-high performance concrete (UHPC),” *Materials*, vol. 14, no. 8, p. 1829, 2021.

[5] Y. Cheng, F. Huang, S. Qi, W. Li, R. Liu, and G. Li, “Durability of concrete incorporated with siliceous iron tailings,” *Construction and Building Materials*, vol. 242, Article ID 118147, 2020.

[6] A. U. Shettima, M. W. Hussin, Y. Ahmad, and J. Mirza, “Evaluation of iron ore tailings as replacement for fine aggregate in concrete,” *Construction and Building Materials*, vol. 120, no. sep.1, pp. 72–79, 2016.

[7] B.-g. Ma, L.-x. Cai, X.-g. Li, and S.-w. Jian, “Utilization of iron tailings as substitute in autoclaved aerated concrete: physico-mechanical and microstructure of hydration products,” *Journal of Cleaner Production*, vol. 127, pp. 162–171, 2016.

[8] Y. Cheng, F. Huang, W. Li, R. Liu, G. Li, and J. Wei, “Test research on the effects of mechanochemically activated iron tailings on the compressive strength of concrete,” *Construction and Building Materials*, vol. 118, pp. 164–170, 2016.

[9] Z.-x. Tian, Z.-h. Zhao, C.-q. Dai, and S.-j. Liu, “Experimental study on the properties of concrete mixed with iron ore tailings,” *Advances in Materials Science and Engineering*, vol. 2016, Article ID 8606505, 9 pages, 2016.

[10] W. Sun, Y. M. Zhang, H. D. Yan, and R. Mu, “Damage and damage resistance of high strength concrete under the action of load and freeze-thaw cycles,” *Cement and Concrete Research*, vol. 29, no. 9, pp. 1519–1523, 1999.

[11] F. N. M. Protasio, R. R. Avillez, S. Letchievsky, and F. Silva, “The use of iron ore tailings obtained from the Germano dam in the production of a sustainable concrete,” *Journal of Cleaner Production*, vol. 278, 2020.

[12] C.-l. Wang, W. Ni, S.-q. Zhang, S. Wang, G.-s. Gai, and W.-k. Wang, “Preparation and properties of autoclaved aerated concrete using coal gangue and iron ore tailings,” *Construction and Building Materials*, vol. 104, pp. 109–115, 2016.

[13] Y. Tan, Y. Zhu, and H. Xiao, “Evaluation of the hydraulic, physical, and mechanical properties of pervious concrete using iron tailings as coarse aggregates,” *Applied Sciences*, vol. 10, no. 8, p. 2691, 2020.

[14] Z. Zhang, Z. Zhang, S. Yin, and L. Yu, “Utilization of iron tailings sand as an environmentally friendly alternative to natural river sand in high-strength concrete: shrinkage characterization and mitigation strategies,” *Materials*, vol. 13, no. 24, p. 5614, 2020.

[15] W. Zhang, Y. Pi, W. Kong et al., “Influence of damage degree on the degradation of concrete under freezing-thawing cycles,” *Construction and Building Materials*, vol. 260, no. 1-2, Article ID 119903, 2020.

[16] D. Wang, X. Zhou, Y. Meng, and Z. Chen, “Durability of concrete containing fly ash and silica fume against combined freezing-thawing and sulfate attack,” *Construction and Building Materials*, vol. 147, pp. 398–406, 2017.

[17] I. G. Colombo, M. Colombo, and M. Di Prisco, “Tensile behavior of textile reinforced concrete subjected to freezing-thawing cycles in un-cracked and cracked regimes,” *Cement and Concrete Research*, vol. 73, pp. 169–183, 2015.