

Research on the Variation law of Compressive Strength of Concrete under the Coupling Effect of Freeze-Thaw and Salt Corrosion

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Abstract: Due to its unique freeze-thaw and sulfate corrosion environment, the northwest region is an important factor causing the deterioration of concrete structures. Compressive strength is a key indicator of the macroscopic performance of concrete. Analyzing the changes in compressive strength of different water cement ratios under complex freeze-thaw environmental conditions is of great guiding significance for improving the service performance of concrete. Therefore, in order to obtain the variation law of compressive strength of concrete under freeze-thaw cycle conditions, this paper designs three water cement ratio concrete freeze-thaw cycle and sulfate solution freeze-corrosion coupling tests to analyze the compressive strength changes at different stages. The results show that in a water freezing and thawing environment, the compressive strength of concrete decreases continuously with the increase of experimental age, and the larger the water cement ratio, the greater the decrease in compressive strength. In sulfate solution freeze-thaw, in the early stage of the experiment, the decrease in compressive strength compared to water freeze-thaw decreased, and in the later stage of the experiment, the decrease increased. The larger the water cement ratio, the greater the impact of the above.

Keywords: Freeze-thaw Cycle; Sulfate Attack; Water/Binder Ratio; Compressive Strength; Indoor Testing.

1. Introduction

The presence of permafrost and seasonal frozen soil layers in cold regions such as the northwest, north China, northeast, and coastal areas has a significant impact on concrete structures and infrastructure. The characteristics of these regions include a large temperature difference between day and night, as well as two necessary conditions for freeze-thaw cycles, namely alternating freeze-thaw cycles and concrete reaching a water retention state. Therefore, in railway, highway, construction and other projects in these areas, freeze-thaw damage is common, which has a serious impact on the frost resistance service life of engineering structures. At the same time, there are a large number of salt lakes distributed in the northwest region [1]. Sulfate ions are widely distributed, which can cause corrosion and damage to concrete structures. Sulfate solution can also have an impact on concrete freeze-thaw, leading to a decrease in compressive strength. Therefore, studying the variation law of compressive strength of concrete under the coupling environment of freeze-thaw and salt corrosion is of great significance for improving the durability of concrete and extending the service life of concrete structures under large temperature difference freeze-thaw cycles and salt corrosion conditions [2-3].

Experts at home and abroad have conducted numerous studies on this type of problem. In the 1940s, T. C. Powers proposed the hydrostatic hypothesis about concrete freeze-thaw damage, pointing out that the freezing of pore water and its subsequent volume expansion are the causes of microcracks and ultimately freezing damage [4]. In 1975, Fagerlund proposed further development of the Powers theory and constructed a mathematical and physical model [5], in which the pressure generated by the smaller pore spacing is greater. In 1953, Power proposed the osmotic pressure

theory based on the hydrostatic pressure hypothesis, which believed that the difference in ion solution concentration in concrete pore solution was the cause of freeze-thaw failure. Deng Xianghui explored the frost resistance of concrete specimens through freeze-thaw experiments and found that increasing the proportion of micropores is beneficial for improving the frost resistance [6]. Zhou David and others independently designed high-strength and low-temperature resistant concrete, and explained the reason why pore water is the cause of freeze-thaw failure through triaxial compression tests under low-temperature freeze-thaw cycles [7]. Lu Chenggong and others designed indoor accelerated tests based on the corrosion, salt erosion, and freeze-thaw damage environment of concrete in western saline soil areas. They analyzed the durability degradation of concrete under the coupling effect of multiple factors, and he believed that freeze-thaw damage was the main durability degradation factor [8]. Xu Cundong et al. conducted in-depth analysis using damage mechanics theory and found that in concrete specimens with different initial damage levels, the damage process occurs earlier than actual loading, and the degree is closely related to the initial damage level. Early freeze-thaw action accelerates the expansion speed of voids and cracks [9]. Yishou Y et al. investigated the degradation mechanism of recycled powder concrete (RPC) under the coupling effect of sulfate freeze-thaw cycles. The degradation degree of RPC was explored by replacing cement with different proportions of recycled brick powder and recycled concrete powder. The results indicate that as the number of freeze-thaw cycles increases and the replacement rate of recycled powder increases, The deterioration of RPC is exacerbated, but the increase of recycled concrete powder has a certain effect on alleviating the deterioration [10]. Wang Yuhang studied the deterioration process of concrete subjected to single-sided freeze-thaw cycles in sulfate environments. Research has

shown that the initial erosion products during freeze-thaw cycles improve the compactness of concrete, but as the products increase, internal pressure leads to accelerated failure [11]. Wang Feng studied the performance changes of carbon nanotube concrete under the coupling effect of sulfate erosion and freeze-thaw cycles. Research has shown that the addition of carbon nanotubes enhances the compressive strength of concrete, which is beneficial for slowing down sulfate corrosion and freeze-thaw damage [12]. In the field of freeze-thaw cycles and freeze-thaw corrosion coupling, scholars at home and abroad have conducted extensive research and achieved fruitful results. However, research from the perspective of the influence of sulfate solutions on concrete freeze-thaw cycles is relatively scarce.

This study is based on experimental exploration of freeze-thaw and salt corrosion environments in the northwest region. The compressive strength of concrete under different freeze-thaw cycles is used as an indicator to analyze the changes in compressive strength of concrete with different water cement ratios under two environmental conditions. Furthermore, the influence of sulfate solution on the freeze-thaw cycle efficiency is studied.

2. Experimental Materials and Methods

2.1. Experimental Raw Materials

The cement used in the experiment was Qilian Mountain brand P O 42.5 ordinary Portland cement, performance indicators are shown in Table 1. The coarse aggregate of concrete is 5-31.5mm continuous particle size crushed stone, with an apparent density of 2670kg/m³; Fine aggregate is made of natural sand with a fineness modulus of 2.9 and an apparent density of 2.60kg/m³ in Zone II; The water source used is laboratory tap water; The water reducer uses a high-performance polycarboxylate water reducer with a water reduction rate of 27%; The solution was prepared using anhydrous sodium sulfate.

Table 1. P. O 42.5 Performance indicators of ordinary Portland cement

| Testing items | Actual measured value | Normative value | |
|-----------------------------|-----------------------|-----------------|-------|
| Loss on ignition (%) | 3.05 | ≤5.0 | |
| Sulfur trioxide content (%) | 2.56 | ≤3.5 | |
| Chlorine ion content (%) | 0.023 | ≤0.06 | |
| Initial setting time (min) | 170 | ≥45 | |
| Final setting time (min) | 230 | ≤600 | |
| Flexural strength | 3d | 5.5 | ≥3.5 |
| | 28d | 8.9 | ≥6.5 |
| compressive strength | 3d | 23.4 | ≥17.0 |
| | 28d | 46.6 | ≥42.5 |

2.2. Preparation and Curing of Experimental Specimens

To ensure that the fluidity of concrete meets the specified requirements, first conduct tests to determine the appropriate amount of water reducing agent. After determining the required amount of materials for each mix proportion of

concrete specimens, the mixing work of concrete materials is carried out. The material consumption per unit volume of concrete in each mix proportion is shown in Table 3. During the concrete mixing process, the coarse and fine aggregates, cementitious materials, water, and water reducing agents are gradually added in order. After each addition of one material, a 30 second mixing is carried out, followed by the addition of the next material. After mixing, pour the concrete into a 100mm x 100mm x 100mm mold pre coated with demoulding oil, and then place it on a vibration platform for vibration. When there is floating slurry on the surface of the concrete and no aggregates are exposed, stop the vibration and treat the surface before standard curing. The specific pouring process is shown in Figure 2. After 24 hours, demould the specimens and continue to maintain them for 28 days before conducting freeze-thaw cycles.



Figure 1. Freeze-thaw test chamber

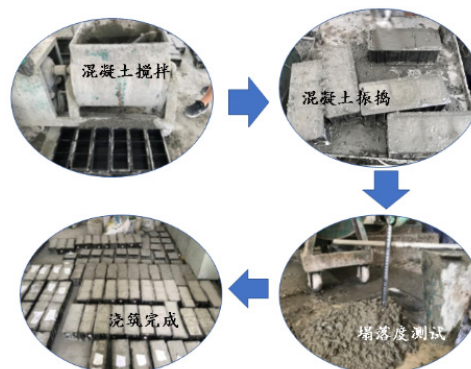


Figure 2. The pouring process of the test block

2.3. Experimental Plan and Process

In order to compare the evolution of compressive strength of concrete with different water cement ratios under freeze-thaw cycle conditions and freeze-corrosion coupling conditions, three mix proportions with water cement ratios of 0.26, 0.32, and 0.38 were set. Using 100mm x 100mm x 100mm concrete specimens as test specimens. The freeze-thaw cycle lifting mechanism is in accordance with the relevant provisions of Section 4 of the "Standard Test Methods for Long term Performance and Durability of Ordinary Concrete" (GB/T 50082-2009) [17] for freeze-thaw cycle testing. After soaking the specimens in advance for 4 days, a large temperature difference freeze-thaw cycle test of concrete is carried out, and the specimens are immersed at least 20mm below the liquid level; After reaching the specified age, dry the surface moisture of the specimen and measure the initial data, then place it in the specimen box. Place the specimen box in the freeze-thaw cycle test box, with the liquid level at least 5mm higher than the concrete; Place the temperature probe at the center of the freeze-thaw cycle

test chamber; To ensure the temperature stability in the freeze-thaw cycle test box under each freeze-thaw environment, the remaining empty spaces are filled with specimen boxes; According to the actual situation in the northwest Ruoqiang region, the concentration of sulfate solution in the freeze-thaw coupling experiment is set at 6%, and other experimental conditions are the same as water freezing and thawing. At the experimental age, conduct concrete compression tests as shown in the figure 3.

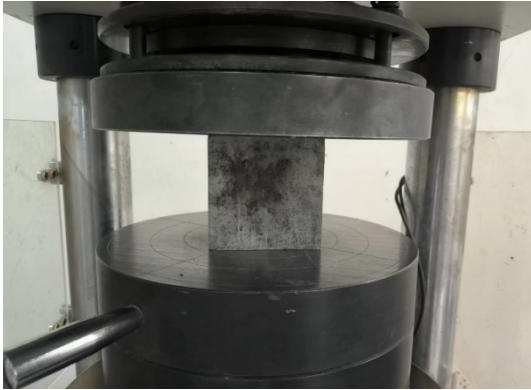


Figure 3. Testing of compressive strength of concrete specimens

The strength parameter adopts the corrosion resistance coefficient as the evaluation index. The corrosion resistance coefficient refers to the ability of concrete specimens to resist freeze-thaw cycle degradation. The ratio of the compressive strength of the n th freeze-thaw cycle of the specimen to the compressive strength of the same batch of specimens before starting freeze-thaw cycles is calculated as follows:

$$K_c = \frac{f_n}{f_0} \quad (1)$$

Where: K_c is the compressive strength and corrosion resistance coefficient of concrete;

f_n is the compressive strength of concrete specimens after the n th freeze-thaw cycle and freeze-thaw cycle(MPa);

f_0 is the compressive strength of concrete specimens after the 0th freeze-thaw cycle and freeze-thaw cycle(MPa).

Table 2. Concrete mix design

| Testing items | Freeze-thaw group | | | Freeze-thaw group | | |
|-----------------------------|-------------------|------|------|-------------------|------|------|
| | A-1 | B-1 | C-1 | A-2 | B-2 | C-2 |
| number | A-1 | B-1 | C-1 | A-2 | B-2 | C-2 |
| Water cement ratio | 0.26 | 0.32 | 0.38 | 0.26 | 0.32 | 0.38 |
| water (kg/m ³) | 150 | 150 | 150 | 150 | 150 | 150 |
| cement (kg/m ³) | 577 | 465 | 395 | 577 | 465 | 395 |
| sand (kg/m ³) | 791 | 764 | 798 | 791 | 764 | 798 |
| stone (kg/m ³) | 967 | 1056 | 1057 | 967 | 1056 | 1057 |
| Water reducing agent(%) | 0.12 | 0.09 | 0.06 | 0.12 | 0.09 | 0.06 |

f_n and f_0 are the arithmetic mean of the compressive strength of the same group (3) of specimens. If the difference between the maximum and minimum values in these three specimens exceeds 15% of the median, the values outside the range need to be excluded and the arithmetic mean of the remaining two values calculated as the final measurement value; If the difference between the maximum and minimum values and the median value exceeds 15% of the median value,

both the maximum and minimum values will be excluded, and the median value will be used as the final measurement value.

3. Experimental Results and Analysis

3.1. Changes in Compressive Strength under Freeze-thaw Cycles

The variation patterns of strength and corrosion resistance coefficient of concrete specimens with water cement ratios of 0.26, 0.32, and 0.38 are shown in Figures 4 and 5.

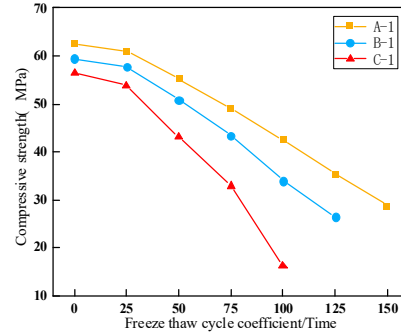


Figure 4. The variation law of compressive strength of concrete

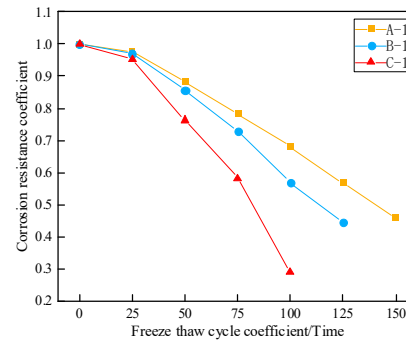


Figure 5. The variation law of concrete corrosion resistance coefficient

According to the data results in Figure 4, the compressive strength of concrete decreases with the onset of freeze-thaw cycles. At 0 cycles, the compressive strength of specimen A-1 is the highest, 1.051 times that of specimen B-1 and 1.107 times that of specimen C-1. The strength of concrete with a smaller water cement ratio is higher. The compressive strength of concrete decreases with the onset of freeze-thaw cycles, which can be roughly divided into two stages. Before 25 cycles, the compressive strength of concrete specimens slowly decreases, Group A-1 decreased by 2.37%, The B-1 group decreased by 3.01%, The C-1 group decreased by 4.79%. After 25 cycles, the compressive strength decreased significantly, Group A-1, The B-1 group and C-1 group specimens failed 175 times, 150 times, and 125 times respectively. At the end of the last test, the compressive strength of each water cement ratio decreased significantly, The A-1 group decreased by 53.98% after 150 attempts, The B-1 group decreased by 55.52% after 125 attempts, The C-1 group decreased by 71.16%, indicating that the higher the water cement ratio, the faster the deterioration rate of concrete and the greater the decrease in compressive strength.

According to the data analysis in Figure 5, as the freeze-thaw period increases, the corrosion resistance coefficient

curve of concrete gradually decreases. Before 25 cycles, the corrosion resistance coefficient of each group of specimens slowly decreased, Group A-1 decreased to 0.98, B-1 group decreased to 0.97, The C-1 group decreased to 0.95, with an overall performance of A-1>B-1>C-1. After 25 cycles, the corrosion resistance coefficients of each concrete showed an accelerated downward trend, and in the last test, the corrosion resistance coefficient of Group A-1 decreased to 0.46, B-1 group decreased to 0.45, The C-1 group decreased to 0.28, with an overall performance of A-1>B-1>C-1, and a decrease in magnitude of C-1>B-1>A-1.

The possible reason for this may be that the cement did not completely hydrate after 28 days of curing, and the freeze-thaw cycle damage was relatively small between 25 cycles. However, the continuous hydration of cement increased its internal density, manifested as a slow decrease in the corrosion resistance coefficient. After 25 cycles, as the test period increases, the damage effect of freeze-thaw on concrete begins to expand. The harmful pores generated by the previous freeze-thaw failure increase, leading to further deterioration, more and more cracks, and an increase in pore water. The degree of deterioration becomes greater, far greater than the growth effect of cement sustained hydration, manifested by an accelerated decrease in the corrosion resistance coefficient. The larger the water cement ratio, the lower the internal density, the larger the porosity, and the more pore water there is. In the early stages of freeze-thaw cycles, the deterioration effect of freeze-thaw is not significant, and the difference in corrosion resistance coefficient is small. With the increase of the approaching period, the more pores there are, the more obvious the degradation effect of freeze-thaw. This vicious cycle is manifested as the larger the water cement ratio, the greater the decrease in corrosion resistance coefficient. The smaller the water cement ratio, the better the frost resistance of concrete.

3.2. The Variation Law of Compressive Strength under Freeze-Thaw Coupling Conditions

The variation patterns of the strength and corrosion resistance coefficient of concrete specimens with water cement ratios of 0.26, 0.32, and 0.38 are shown in Figures 6 and 7.

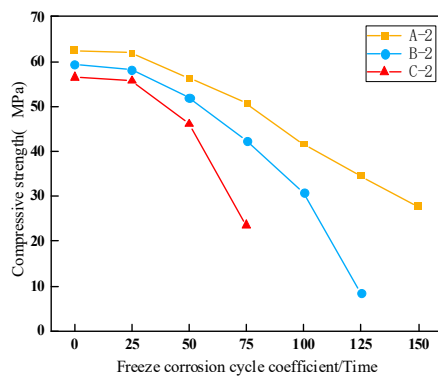


Figure 6. The variation law of compressive strength of concrete

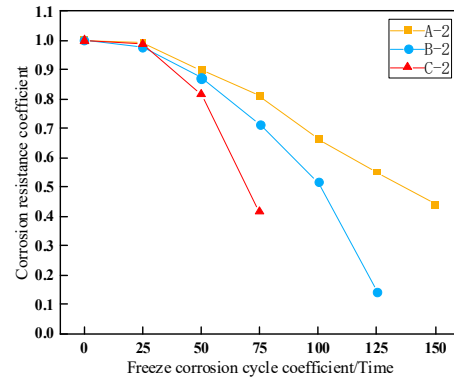


Figure 7. The variation law of concrete corrosion resistance coefficient

According to the data results in Figure 6, the variation pattern of compressive strength of concrete under sulfate solution freeze-thaw environment is basically consistent with that of water freeze-thaw environment. Before 25 freeze-thaw cycles, the compressive strength slowly decreases, Group A-2 decreased by 0.83%, The B-2 group decreased by 2.11%, The C-2 group decreased by 1.22%, and after 25 cycles, the compressive strength decreased significantly, A-2 groups, The B-2 group and C-2 group specimens failed 175 times, 150 times, and 100 times respectively. At the end of the last test, the compressive strength of each water cement ratio decreased significantly, The A-1 group decreased by 55.80% after 150 attempts, The B-1 group decreased by 85.38% after 125 attempts, The C-1 group decreased by 58.30%.

Compared with the water freezing and thawing environment, the compressive strength gradually decreases during the stage, and the degree of decrease in compressive strength of each group of specimens is relatively small, The decrease in A-2 group decreased by 1.54%, The decrease in B-2 group decreased by 0.90%, The decrease in C-2 group decreased by 3.57%. In the stage of rapid decrease in compressive strength, the degree of decrease in compressive strength of each group of specimens is relatively large, After 150 cycles, the decrease in Group A-2 increased by 1.82%, The decrease in B-2 group increased by 5.05% after 100 cycles, The C-2 group experienced a reduction from 125 failures to 100 failures, and at 75 cycles, the decrease increased by 16.54%.

According to the data analysis in Figure 7, the variation pattern of concrete corrosion resistance coefficient under sulfate solution freeze-thaw environment is basically consistent with that of water freezing and thawing. Before 25 cycles, the corrosion resistance coefficient of each group of specimens slowly decreased, Group A-2 decreased to 0.991, B-2 group decreased to 0.987, The C-2 group decreased to 0.987. After 25 cycles, the corrosion resistance coefficients of each concrete showed an accelerated downward trend, and in the last test, the corrosion resistance coefficient of Group A-2 decreased to 0.441, B-1 group decreased from 0.519 after 100 cycles, The C-2 group had 75 cycles as the final deadline, which decreased to 0.416.

Compared with the water freezing and thawing environment, the corrosion resistance coefficient of each group of specimens increased after 25 sulfate freeze-thaw cycles, Group A-2 increased by 1.5%, The B-2 group increased by 0.9%, The C-2 group increased by 3.5%,

manifested as C-2>A-2>B-2. After 25 cycles of sulfate freeze-thaw, the corrosion resistance coefficients of each group of specimens decreased during the same testing period. Overall, in sulfate freeze-thaw environments, concrete specimens perform well in the early stages of freeze-thaw cycles, while in the later stages of freeze-thaw cycles, degradation is more severe.

The possible reason for this may be that in the early stage of freeze-thaw cycles, in addition to continuous hydration of cement, sulfate solutions enter the interior of the concrete along the connected pores, and their physical crystallization and chemical corrosion products also improve the compactness of the concrete. Compared with water freeze-thaw cycles of the same age, the compactness is increased. At the same time, sulfate solutions may cause a decrease in pore water solution, which to some extent weakens the degree of freeze-thaw damage. Overall, this has led to a relative improvement in frost resistance. The larger the water cement ratio of concrete, the larger the pores, and the more sulfate enters, resulting in a relatively high increase in internal density, leading to the maximum increase in the corrosion resistance coefficient of Group C-2. In the later stage of freeze-thaw cycles, the continuous accumulation of erosion products and sulfate crystals causes damage to the pore walls, which, in combination with the freeze-thaw damage effect, leads to more severe deterioration of concrete. Overall, the corrosion resistance coefficient of concrete decreases more significantly than that of water freeze-thaw cycles.

4. Conclusion

Through the freeze-thaw cycle and salt corrosion coupling test of concrete with different water cement ratios, the following main conclusions have been obtained:

(1) As the number of freeze-thaw cycles increases, the compressive strength and corrosion resistance coefficient of concrete with different water cement ratios change significantly, both showing a slow decline at first and then an accelerated decline trend. The larger the water cement ratio, the more significant the decrease in compressive strength.

(2) Compared to water freezing and thawing, the trend of compressive strength change of concrete in sulfate solution freeze-thaw environment is the same. However, in the stage of slow decline in compressive strength, the decrease in sulfate solution freeze-thaw decreases, while the decrease increases in the later stage, indicating that sulfate solution has an inhibitory effect on freeze-thaw cracking in the early stage of the experiment, and an aggravating effect in the later stage. The larger the water cement ratio, the more obvious this effect.

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