Study on Freeze-Thaw Relationship of Concrete under Laboratory and Natural Conditions

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Abstract: Through field sampling and testing, the relationship between the number of freeze-thaw cycles of hydraulic concrete in actual environment and number of freeze-thaw cycles under laboratory conditions is established to solve the problem that the structure durability of hydraulic concrete in Jilin Province is degraded due to freeze-thaw damage. In this way, people can predict the number of concrete cycles in the actual engineering environment through freeze-thaw cycle parameters in laboratory tests, and put forward an economical and reasonable management and operation plan, which is of great significance in engineering.

1. Introduction
With the construction of Xiluodu and Xiangjiaba hydropower projects in Jinsha River, the installed hydropower capacity in China reached 280.02 million kw in 2013, accounting for 22.45% of the total installed electricity capacity. According to China’s “National Plans for Responding to Climate Change”, the clean energy such as hydropower must be developed vigorously to achieve the goal of reducing the carbon emission by 40%-45% in 2020 compared with 2005. With the national investment in water infrastructure, a large number of reservoirs and irrigation facilities have been built. Concrete material is one of the commonly used materials in water conservancy and hydropower engineering. The durability of hydraulic concrete has become the main factor affecting the service life of water conservancy projects [1-5].

The reservoir in Tonghua City of Jilin Province was sampled on site. Based on the freeze-thaw test of concrete, the relationship between the freeze-thaw times of hydraulic concrete in the actual environment and freeze-thaw times under laboratory conditions is established, and then the freeze-thaw damage of concrete is judged, and the economic and reasonable operation and management scheme is put forward, in order to provide reference and improvement basis for water conservancy projects in nearby areas.

2. Field Sampling
In the reinforcement project of Tonghua Songtun Reservoir, the main part of the reservoir which has been in operation for 37 years was demolished and rebuilt. Samples were selected from the debris produced during the demolition process, and the selected samples were mainly located in the bottom board of sluice. After that, the samples were drilled and cored. The dynamic elastic modulus and ultrasonic velocity of the cored samples were measured. According to the calculation of the dynamic elastic modulus of cylindrical concrete, the dynamic elastic modulus of the two samples were 40.72GPa and 43.06GPa, respectively. The ultrasonic velocity of samples was measured by HC-U7 non-metallic ultrasonic detector, and the results were 4.089km/s and 4.457km/s, respectively.
3. Laboratory Test

3.1. Test Raw Materials
- Cement: P.O42.5 cement produced by Jilin Yatai Cement Co., Ltd.
- Fly ash: Class I fly ash produced by a power plant in Changchun.
- Silicon powder: The density of silicon powder was 2.20g/cm3, and the content of SiO2 was 92%.
- Coarse aggregate: Continuously graded gravel of 4.75~31.5mm.
- Fine aggregate: River sand with the fineness modulus of 3.05, the mud content of 2.3%, and the bulk density of 1.433kg/m3.
- Additives: SK air entraining and water reducing admixture of Dahua Building Materials Chemical Co., Ltd.
- Mixing water: Changchun tap water.

3.2. Test Instruments
The freeze-thaw test of concrete mainly involves rapid freeze-thaw test and unilateral freeze-thaw test.

The main instruments in rapid freeze-thaw test included SKDR-28S automatic rapid freeze-thaw tester for concrete, DT-18 dynamic elastic modulus tester and HC-U7 non-metallic ultrasonic tester.

The main instruments in unilateral freeze-thaw test included NJ-HDD-II concrete unilateral freeze-thaw tester and HC-U7 non-metallic ultrasonic detector.

3.3. Test Method

3.3.1. Rapid Freeze-Thaw of Concrete. The frost-resisting specimens in the rapid freeze-thaw test of concrete were the prisms of 100 mm×100 mm×400 mm. The specimens were immersed in water at (20±2) °C four days before reaching the test age, and then the test was carried out.

If one of the following three conditions occurred, the test would be stopped:
- The number of freeze-thaw cycles reached the predetermined number of cycles.
- The relative dynamic elastic modulus decreased to 60% of the initial value.
- The rate of mass loss was 5%.

3.3.2. Unilateral Freeze-Thaw of Concrete. The frost-resisting specimens in the unilateral freeze-thaw test of concrete were prisms of 150 mm×150 mm×70 mm. After specimens were formed, they were cured for 24 hours with moulds, and then the specimens were cured to 2~4 days before the age of 28 days. After curing, the impurities on the surface of specimens were removed and the mass of specimens was measured. Then the four outer surfaces of specimens were sealed with epoxy resin. The upper and lower surfaces were not treated. Before the test, the water pre-absorption time of the specimen was maintained for 7 days, and the temperature was maintained at 20°C±2°C. If one of the following three conditions occurred, the test would be stopped:
- Reaching 28 freeze-thaw cycles.
- When the total mass of exfoliated material per unit surface area was more than 1500g/m2.
- When the ultrasonic relative dynamic elastic modulus of the specimens was reduced to 80% [6-7].

3.4. Analysis of Test Results

3.4.1. Rapid Freeze-Thaw of Concrete. Fig.1 is the mass loss rate of rapid freeze-thaw test of concrete, Fig.2 is the relative dynamic elastic modulus of rapid freeze-thaw test of concrete, and Fig.3 is the ultrasonic velocity of rapid freeze-thaw test of concrete.
3.4.2. Unilateral Freeze-Thaw of Concrete. Fig. 4 shows the mass loss per square meter in unilateral freeze-thaw test of concrete, and Fig. 5 shows the ultrasonic relative dynamic elastic modulus in unilateral freeze-thaw test of concrete.

3.4.3. Analysis of Test Results. According to the rapid freeze-thaw test, the following conclusions are drawn: In the rapid freeze-thaw test and unilateral freeze-thaw test, the addition of admixtures and additives has a very significant impact on the results. At the end of the test, the mass loss rate, relative dynamic elastic modulus, ultrasonic velocity and mass loss per square meter of the specimen group with additives and admixtures were better than those without additives and admixtures.
4. Analysis of Freeze-Thaw Relationship of Hydraulic Concrete under Laboratory and Natural Conditions

4.1. The Theory or Method for Establishing the Relationship between the Two
To establish the freeze-thaw relationship of hydraulic concrete under laboratory and natural conditions, the relationship between freeze-thaw test data and freeze-thaw times is firstly established by regression analysis. The specific regression analysis method is the least square method. The least square method is a mathematical optimization technique, which minimizes the square of error to find the best function matching. Using the least square method, the unknown data can be easily obtained and the sum of squares of errors between the obtained data and the actual data can be minimized. Its main advantages are that it can be displayed, can be expressed by formulas, and can be easily implemented by a simple computer program, so this analysis method is adopted.

4.2. Freeze-Thaw Relationship of Hydraulic Concrete under Laboratory and Natural Conditions
During the test, the dynamic elastic modulus and ultrasonic velocity of C25 specimen group are used to establish the freeze-thaw relationship of hydraulic concrete under laboratory and natural conditions in Jilin area. Firstly, the least square method in Matlab regression analysis is used to fit the dynamic elastic modulus and the ultrasonic velocity nonlinearly. The relationship formula between the number of freeze-thaw cycles and the dynamic elastic modulus and between the number of freeze-thaw cycles and the ultrasonic velocity can be obtained. The relationship between the number of freeze-thaw cycles and the actual number of freeze-thaw cycles under natural conditions can be obtained by substituting the dynamic elastic modulus and ultrasonic velocity of samples into the formula.

- The relation formula between the number of rapid freeze-thaw cycles and dynamic elastic modulus. Specific formulas and fitting curves are as follows:
  \[ E = -9.772 \times 10^{-5} \times N_r^2 + 3.052 \times 10^{-3} \times N_r + 45.22 \]  
  (1)

In the equations, \( N_r \) is Rapid freeze-thaw cycle of concrete specimens (number); \( E \) is the Dynamic elastic modulus (GPa).

- The relation formula between the number of rapid freeze-thaw cycles and the ultrasonic velocity. The specific formula and fitting curve are as follows:
  \[ v_r = 5.039 \times e^{-((N_s+83.27)/880.9)^2} \]  
  (2)

In the equations, \( v_r \) is Ultrasonic velocity(km/s).

- The relation formula between the number of unilateral freeze-thaw cycles and the ultrasonic velocity. The specific formula is as follows:
  \[ v_s = 5.777 \times e^{-((N_s+57.71)/143.6)^2} \]  
  (3)

In the equations, \( N_s \) is the Unilateral freeze-thaw cycle of concrete specimens (number); \( v_s \) is the Ultrasound velocity of unilateral freeze-thaw (km/s).
Figure 8. The relation curve of ultrasonic velocity

The least square method of regression analysis is used to fit the relationship between the number of freeze-thaw cycles and dynamic elastic modulus. The correlation coefficient is greater than 0.96, which shows that the fitting curve can truly reflect the test results.

By putting the dynamic elastic modulus of specimens into the established relation formula of the number of rapid freeze-thaw cycles and the dynamic elastic modulus, the comparison of indoor and outdoor freeze-thaw times is 1:17.8, and 1:25.1. There are some differences between the two groups of data and the comparison data between indoor and outdoor freeze-thaw cycles established by Li Jinyu. The main reason is that Li Jinyu did not use the cored samples in reservoirs which have been running for many years to establish the relation formula. Different samples in natural environment will have a certain impact on the results [8-9]. According to the relation formula between the number of rapid freeze-thaw cycles and the dynamic elastic modulus, the decrease of the dynamic elastic modulus of concrete specimens will be aggravated with the progress of the test. In the first 100 cycles, the damage speed of concrete is slow, only decreasing by 3%. After 200 cycles, the damage speed of concrete is faster, and the dynamic elastic modulus decreases by 10% in 200 to 300 cycles.

According to the relation formula between the number of unilateral freeze-thaw cycles and the ultrasonic velocity, the ultrasonic velocity of unilateral freeze-thaw decreases more averagely during the test. The ultrasonic velocity loss of the first 14 cycles is 47% of the total loss. It can be considered that the internal damage of unilateral freeze-thaw increases steadily with the increase of freeze-thaw cycles.

5. Conclusions
• In the rapid freeze-thaw test and unilateral freeze-thaw test, the frost resistance of concrete specimens will be improved obviously by adding fly ash, silicon powder and air entraining and water reducing admixture.
• The change of ultrasonic velocity of specimens in 310 rapid freeze-thaw tests and 28 unilateral freeze-thaw tests is the same. Except for C20 specimen group, the decrease of ultrasonic velocity in the same specimen group is less than 0.04 km/s.
• By putting the dynamic elastic modulus of specimens into the established relation formula of the number of rapid freeze-thaw cycles and the dynamic elastic modulus, the comparison of indoor and outdoor freeze-thaw times is 1: 17.8 and 1: 25.1.
• According to the comparative analysis of indoor and outdoor freeze-thaw times, it’s known that for small reservoirs in Jilin area, the freeze-thaw damage speed of the bottom board of sluice is slow in the early stage of operation, and the dynamic elastic modulus is almost unchanged. After a certain number of years, the freeze-thaw damage will accelerate sharply, which requires managers to monitor the concrete of the reservoir constantly to prevent the sudden damage of concrete from causing greater losses. However, for the concrete in the ice-salt environment and the water level changing area, the damage increases steadily with the increase of freeze-thaw times, so monitoring
should be strengthened, and the speed of freeze-thaw damage should not be neglected because of the short operation time.

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