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EXPERIMENTAL STUDY ON DYNAMIC ELASTIC MODULUS AND BONDING PROPERTIES OF REINFORCED CONCRETE BRIDGE DECK PANELS IN SALT-FREEZE ENVIRONMENT

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ABSTRACT

Reinforced concrete structures are the most widely used structural form today. In the western salt-alkali areas and in road and bridge engineering environments where de-icing agents are used in the northern regions, chloride ions penetrate the concrete, causing steel reinforcement to lose its passivation and corrode, resulting in durability damage to the reinforced concrete structure. Among all bridge components, the bridge deck panels of reinforced concrete bridges are most severely and directly affected by salt-frost damage. Predicting the service life under salt-frost conditions is an urgent issue to be addressed in the durability design, evaluation, and structural maintenance decision-making of reinforced concrete bridge deck panels. In this study, 15 beam specimens and 75 steel reinforcements were subjected to freeze-thaw tests, and 300 freeze-thaw cycles were performed on the concrete beam specimens to analyze the variation of their dynamic elastic modulus. Freeze-thaw tests were conducted on the steel reinforcement specimens with freeze-thaw cycles of 50 times, 100 times, and 150 times. After the freeze-thaw tests, pull-out tests were conducted to measure the changes in bond strength between the steel reinforcement and concrete, relative slip between the steel reinforcement and concrete, and other data.

KEYWORDS

Salt-frost, Freeze-thaw cycles, Dynamic elastic modulus, Bond stress

INTRODUCTION

Bridge is an important part of highway traffic and plays an important role in highway transportation. With the continuous development of social economy and increasingly busy traffic, Bridges are playing an irreplaceable role as the throat of highway traffic [1-3]. Due to environmental and geographical conditions, high latitudes are prone to heavy snow and freezing weather. While the extensive use of chloride-based snow-melting agents has effectively alleviated the pressure on transportation, it has also caused devastating damage to concrete infrastructure [4]. The erosion and damage of concrete by salt are the combined result of physical and chemical actions. While soluble inorganic salts such as NaCl and $CaCl_2$ can be spread on road surfaces to prevent icing, long-term research and observation suggest that salt exacerbates surface erosion of concrete. The physicochemical action and corrosiveness of snow-melting agents are strong and can cause chronic damage to bridge decks [5-8].

The deterioration factors of concrete are sorted according to the degree of influence, and the

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results are as follows: steel corrosion, freezing damage and invasion in cold environment physicochemical action of corrosion environment [9]. The hydration reaction of cement in concrete and the alkali-aggregate reaction produce alkaline substances that form a dense passivation film around the steel bars, thus protecting the steel bars. When subjected to carbonization and chloride ion erosion, the basic substances of the passivation film on the surface of the steel bar will be consumed due to chemical reactions. In the case that the passivation film is destroyed, the rebar will form a galvanic cell with ions, oxygen and water in the concrete pore solution and occur electrochemical corrosion, thus the tensile strength is greatly reduced. [10-12]. With the increase of the number of freeze-thaw cycles, the cracks inside concrete and along the contact surface of aggregate and cement paste increase, and the strength, modulus and Poisson's ratio of concrete decrease. In winter in cold regions, bridge structures and concrete structures in pavement where deicing salt is released are exposed to chlorine salt erosion environment and are subjected to low temperature freezing. This will not only cause the low temperature freezing damage of concrete, but also accelerate the corrosion of steel bars due to the intensification of chloride ions, which is the most serious form of deterioration of reinforced concrete structures [14].

There is a lack of comprehensive research and evaluation regarding the harmful effects of snow-melting agents on highways and bridges in China and even in developed countries. The evaluation of the corrosive nature of snow-melting agents lacks a reasonable methodology and a standardized evaluation system. In addition to the common peeling failure and quality loss of concrete, the changes of the elastic modulus and bonding properties of concrete induced by chloride corrosion and freeze-thaw cycle need to be further studied. Therefore, it is necessary to study the change of elastic modulus parameters of concrete under chloride ion erosion and freeze-thaw cycle [15-16].

The change of dynamic elastic modulus caused by internal damage of reinforced concrete was obtained through continuous ultrasonic test. The influence of internal damage on the bond property of steel bar and concrete is obtained by tensile test between steel bar and concrete. The dynamic elastic modulus of concrete and the variation law of bond stress between reinforcement and concrete are studied, which provides theoretical basis and technical support for the design department to carry out durability design of concrete deck in cold area. It also serves as a foundation for traffic management departments in controlling the use of snow-melting materials, evaluating their harmful effects on highways and bridges, and predicting their service life.

DETERMINATION OF DYNAMIC MODULUS VARIATION OF SALT-FROZEN SPECIMENS

Experimental summary

The dynamic modulus is an important indicator for assessing the freeze-thaw damage of reinforced concrete and is also a key parameter in evaluating the durability lifespan of reinforced concrete structures. It effectively reflects the degree of internal damage within specimens.

Fig. 1 - Layout diagram of test specimens

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1. *Sample preparation and grouping*

The dimensions of the specimens were 100 mm×100 mm×400 mm, with a protective layer thickness c of 15 mm. There were a total of 15 specimens, out of which 3 were control specimens. The remaining 12 specimens were divided into 4 groups. The first group was labeled as B11-1 to B11-3, the second group as B12-1 to B12-3, the third group as B21-1 to B21-3, and the fourth group as B22-1 to B22-3. Each group was filled with different liquids during the freeze-thaw cycles: water, NaCl solution, A solution, and B solution.

There are four types of immersion solutions, including water, NaCl solution, a solution with a mass ratio of NaCl: $MgCl_2$: $CaCl_2$=6:2:2, and a solution with a mass ratio of NaCl: $MgCl_2$: $CaCl_2$=6:3:1. The concentration of each solution is 3%. For convenience, the solution with a mass ratio of NaCl: $MgCl_2$: $CaCl_2$=6:2:2 is defined as solution A, and the solution with a mass ratio of NaCl: $MgCl_2$: $CaCl_2$=6:3:1 is defined as solution B.

2. *Test equipment*

This experiment adopts the rapid freezing method, where the specimens are frozen and thawed in a solution or water. The Beijing Naiheng Science and Technology’s Durable Ace Series of Concrete Rapid Freeze-Thaw Test System is used. The dynamic elastic modulus tester used is the DT-18W Dynamic Modulus Tester produced by Tianjin Beichen Construction Testing Instrument Factory. The freeze-thaw system and testing system are shown in Figure 2 - Figure 3.

Fig. 2 – Freeze-thaw cycling system

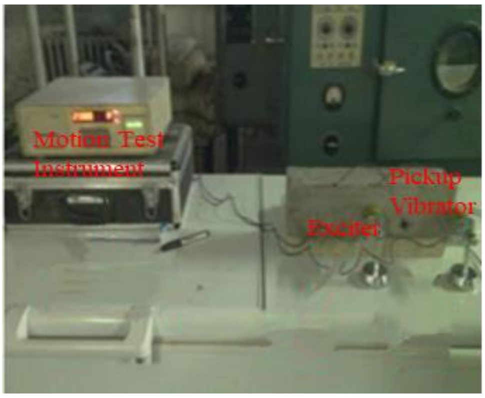

Fig. 3 – Dynamic elastic modulus testing system

3. *Dynamic modulus testing procedure*

(1) Measure the mass of the test specimen with an accuracy of 0.01 kg and measure its dimensions with an accuracy of 1 mm.

(2) Place the specimen on a prepared foam plastic board, with the molded surface facing upwards. The thickness of the foam plastic board should be between 30 mm and 50 mm.

(3) Adjust and secure the exciter and the pickup transducer at the desired heights. Apply a thin layer of Vaseline to the end of the measuring rod of the exciter, and gently press it against the center of the specimen’s side surface. The measuring rod of the pickup transducer should be gently pressed against the side surface at a distance of 5 mm from the top/bottom surface.

(4) Once the adjustments are complete, enter the parameters such as mass, edge length, etc. into the elastic modulus testing device. Press the “Confirm” button, and then press the “Test” button to start data acquisition.

(5) After the readings are completed, gently press the measuring rod of the pickup transducer against the side surface at a distance of 5 mm from the bottom/top surface. Repeat the steps from 4, take another set of data, and calculate the average value of the two sets of data. Perform this

measurement every 25 freeze-thaw cycles, until a total of 300 freeze-thaw cycles are completed or until the relative dynamic elastic modulus drops below 60%.c

Test results and discussion

The test results of dynamic elastic modulus during the freeze-thaw process of the specimens are shown in Table 1 and Figure 4.

Tab. 1 - Test results of dynamic elastic modulus (Unit: MPa)

Immersion liquid	Number of Cycles												
	0	5	10	15	20	25	50	75	100	125	150	175	200
Water	1.40	0.23	6.68	2.35	3.16	9.34	8.89	9.46	9.06	7.62	6.48	4.84	3.34
NaCl	2.24	0.52	1.24	0.04	0.08	7.08	5.82	6.23	6.35	2.75	0.37	9.12	8.06
Solution A	9.91	0.24	9.73	9.25	9.05	6.56	4.42	4.80	3.59	0.18	7.69	6.12	5.43
Solution B	9.47	9.64	8.37	6.81	6.81	4.02	3.34	3.45	3.06	9.37	7.30	5.84	4.68

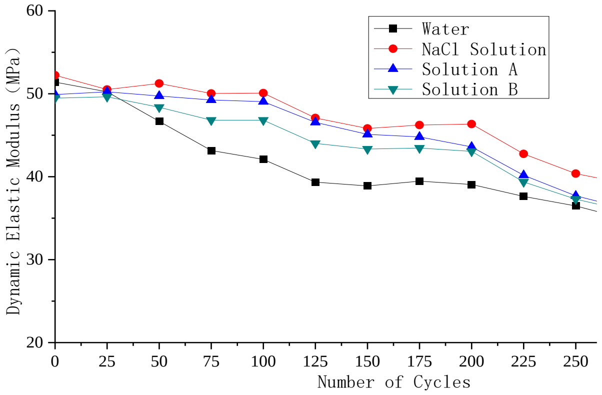

Fig. 4 – Line graph of dynamic modulus test results (unit: MPa)

The calculated values of the dynamic modulus of each specimen at freezing-thawing cycles of 0, 25, 50… 275, and 300 times, as well as the comparison between the calculated values and the measured values of the dynamic modulus of the specimens, are shown in Figure 5 - Figure 8.

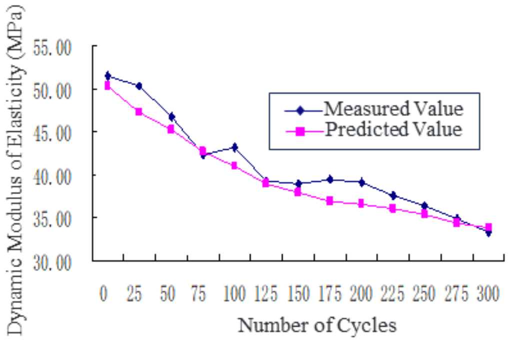

Fig. 5 – Specimen in water

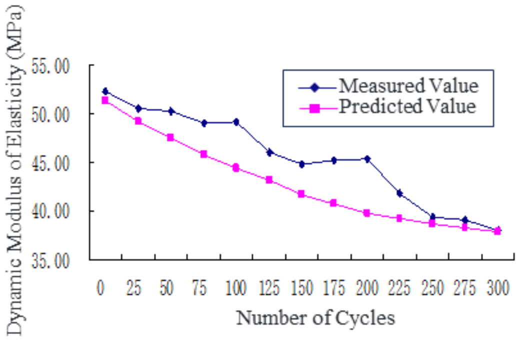

Fig. 6 – Specimen in NaCl solution

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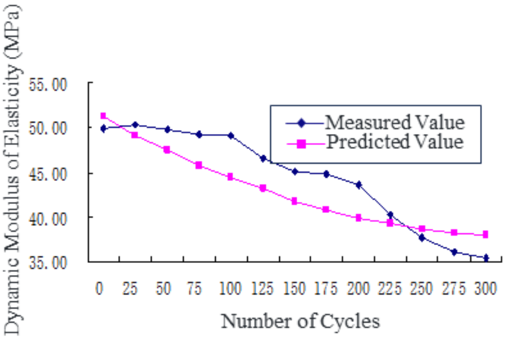

Fig. 7 – Specimen in solution A

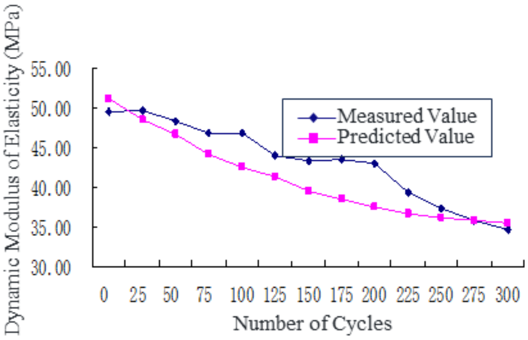

Fig. 8 – Specimen in solution B

Based on Figure 5 - Figure 8, it can be observed that the variations of the dynamic modulus of elasticity in water and the respective solutions generally follow a 4th degree polynomial curve. Taking into account factors such as experimental conditions and instrument errors, the trend of the calculated values aligns well with the measured values. Occasionally, there are outliers in the measured curve, but they fall within the acceptable range of error.

Unlike the effect of Cl- on the loss of concrete quality, to some extent, Cl- actually inhibits the decay of dynamic modulus of elasticity during freeze-thaw processes, but it does not prevent it entirely. By examining the decay curves of the dynamic modulus of elasticity for different groups of specimens, it can be observed that Cl- solutions of different concentrations have varying degrees of inhibition on the decay process. There exists a critical concentration of Cl- that exhibits the strongest inhibitory effect, resulting in the least loss of dynamic modulus of elasticity in the specimens. When the Cl- concentration exceeds or falls below this critical value, the decay of the dynamic modulus of elasticity intensifies, but it remains lower than the decay value observed in water.

The relative dynamic modulus values after 300 freeze-thaw cycles confirm this argument, as demonstrated in Figure 9 and Figure 10.

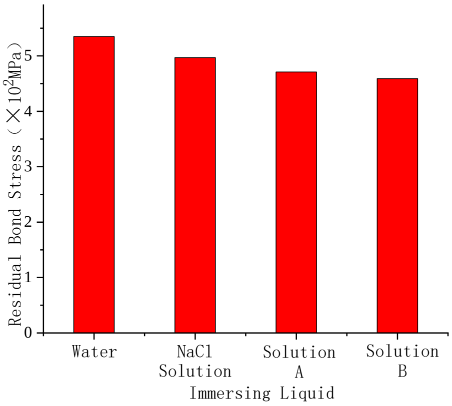

Fig. 9 – Relative dynamic modulus of specimens after 150 cycles

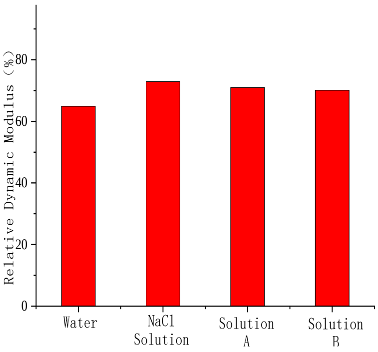

Fig. 10 – Relative dynamic modulus of specimens after 300 cycles

It can be observed that the relative dynamic elastic modulus of the specimens in water is substantially lower than those in various solutions after 150 and 300 cycles. The relative dynamic elastic modulus of the specimens in the solutions decreases with increasing concentration, but the difference is not significant. After 150 cycles, the relative dynamic elastic modulus of the specimens in water is 84% of that in the NaCl solution, 85% of that in solution A, and 86% of that in solution B.

After 300 cycles, the relative dynamic elastic modulus of the specimens in water is 89% of that in the NaCl solution, 92% of that in solution A, and 93% of that in solution B.

According to the theoretical formula derived from fitting the experimental values using Matlab analysis software, it can be calculated that the specimens in water will reach the failure limit after 316 freeze-thaw cycles, with a relative dynamic elastic modulus of 59.6% at failure.

STUDY ON BOND STRESS BETWEEN SALT-FROZEN CONCRETE AND REINFORCEMENT

Experiment summary

Salt intrusion and freeze-thaw environments can cause concrete carbonation and corrosion of internal reinforcement, thereby affecting the bond performance between reinforcement and concrete. This hinders the full utilization of the comprehensive mechanical properties of reinforced concrete materials and affects the safety and service life of structures. The variation in bond performance between steel and concrete is an important aspect in studying the load-bearing capacity and durability of reinforced concrete structures. There are multiple factors that influence bond performance, and the current theoretical research is not yet comprehensive, research findings are not systematic, and research methods are not sufficiently scientific.

The main cause of protective layer cracking during pull-out is the mechanical interlocking force between steel and concrete. By using smooth round bars, concrete cracking can be avoided, leading to a better understanding of the bond-slip constitutive relationship after salt freezing. There are various research methods both domestically and internationally in this area, which can be roughly divided into three types: local bond stress-slip tests, beam-like tests, and center pull-out tests. The center pull-out test is characterized by its simplicity of operation and accurate data, therefore we have decided to adopt the center pull-out test method.

1. Testing equipment

Fig. 11 – Pull-out test loading and data acquisition system

The testing machine used is the WA-600B hydraulic universal testing machine produced by Wuxi Xinluda Company. Force control loading is employed with a loading rate of 0.03 KN/s. Due to the original fixtures being unable to secure the specimens of this model, customized fixtures were designed to secure the specimens. The free-end displacement is measured using a dial gauge, and steel reinforcement strain is measured using strain gauges. The signal is received through lead wires by the BZ2208-A static strain force transducer, using a half-bridge signal reception mode.

2. Test specimen preparation

The cross-sectional dimensions of the specimen are 100 mm × 100 mm × 100 mm. The steel reinforcement selected is polished round steel reinforcement with a nominal diameter of 10 mm. The mechanical properties of the steel reinforcement are presented in Table 2.

Tab. 2 - Steel reinforcement properties for tensile test specimens

Strength Grade	Rebar Type	Nominal Diameter （mm）	Yield Strength f_y （MPa）	Ultimate Strength f_u （MPa）	Elongation δ_{10} （%）
HPB235	Smooth Round Steel Bar	10	235	425	23

A total of 75 tensile test specimens were prepared, of which 3 were control specimens for comparative purposes. The remaining 72 specimens were divided equally into 6 groups, as shown in Table. 3. In this chapter, specimens subjected to 50, 100, and 150 freeze-thaw cycles were selected for experimental study, while the remaining specimens are reserved for the next chapter's research.

Tab.3: - Tensile Test Specimen Grouping

Immersion Liquid	Freeze-Thaw Cycle Count					
	25Times	50Times	75Times	100Times	125Times	150Times
Water	L1-1~3	L2-1~3	L3-1~3	L4-1~3	L5-1~3	L6-1~3
NaCl	L7-1~3	L8-1~3	L9-1~3	L10-1~3	L11-1~3	L12-1~3
Solution A	L13-1~3	L14-1~3	L15-1~3	L16-1~3	L17-1~3	L18-1~3
Solution B	L19-1~3	L20-1~3	L21-1~3	L22-1~3	L23-1~3	L24-1~3

Experimental results and discussion

1. Mode of failure

Based on previous test experience, the failure modes of the center pull-out specimens in reinforced concrete can be categorized into three types: (1) shear-sliding failure, (2) concrete splitting failure, and (3) an intermediate failure between the two. Shear-sliding failure occurs when the mechanical interlocking force between steel and concrete is relatively weak, and the bonding stress is primarily dependent on the chemical adhesion between steel and concrete. In the test, significant relative displacement occurs between the steel reinforcement and concrete, while the concrete remains intact. This type of failure is commonly observed in smooth round steel specimens. Concrete splitting failure primarily arises when the mechanical interlocking.

The specimens in this study were prepared using smooth round steel bars, and it was found that the failure mode of the pull-out test specimens was consistently shear-sliding failure, with the concrete remaining intact. Some specimens exhibited minor concrete damage at the free end, but no rusting was observed in the internal steel reinforcement. Three untreated control specimens were subjected to pull-out tests, resulting in an average ultimate pull-out load of 32.43 KN and a residual pull-out load of 4.6 KN. The failure modes of the pull-out specimens are shown in Figure 12 - Figure 15.

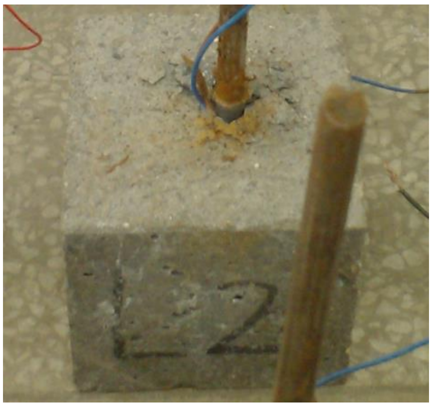

Fig. 12 – Failure mode of specimen L2

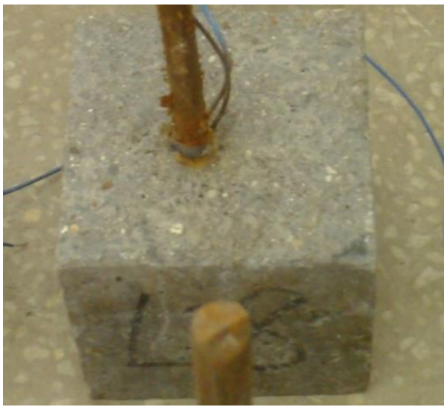

Fig. 13 – Failure mode of specimen L8

Fig. 14 – Failure mode of specimen L10

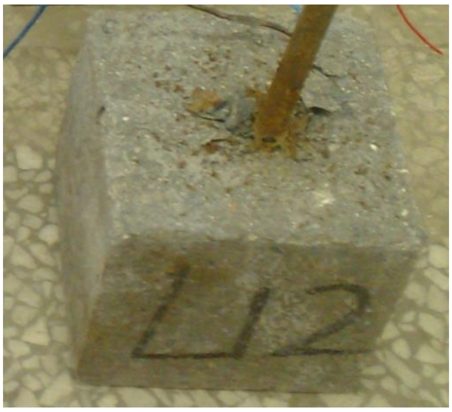

Fig. 15 – Failure mode of specimen L12

2. Bond-Slip Curve

During the testing process, the hydraulic loading control system can directly read the applied tensile load and then calculate the bond stress between steel and concrete τ : $\tau = 4P/(\pi D^2 l)$, D represents the diameter of the steel reinforcement, l represents the embedded length of the steel reinforcement in the concrete. The readings from the dial gauge and strain gauge can be used to calculate the slip distance S between the steel reinforcement and the concrete. This allows the relationship curve between the bond stress τ and slip distance S after 50, 100, and 150 freeze-thaw cycles to be obtained. The bond-slip curve provides a visual representation of the bond behavior between steel reinforcement and concrete, making it useful for analyzing changes in the bond performance under different test conditions.

The bond-slip curves of each specimen under the same number of freeze-thaw cycles but different immersion liquids are shown in Figure 16 – Figure 17.

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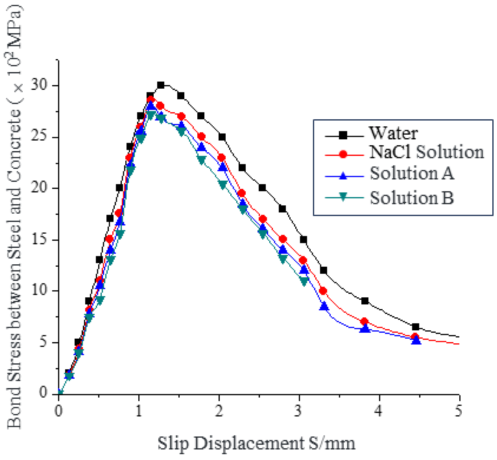


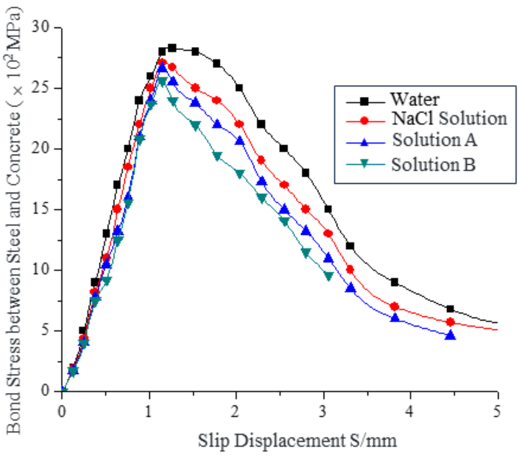
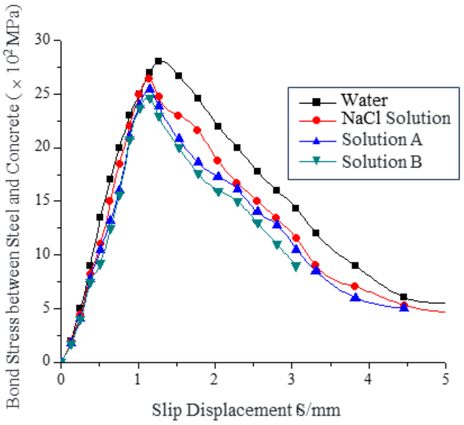


Fig. 16 – Bond-slip curve after 50 freeze-thaw cycles

Fig. 17 – Bond-slip curve after 100 freeze-thaw cycles

The bond-slip curves of each specimen under the same immersion liquid but different numbers of freeze-thaw cycles are shown in Figure 18 – Figure 19.



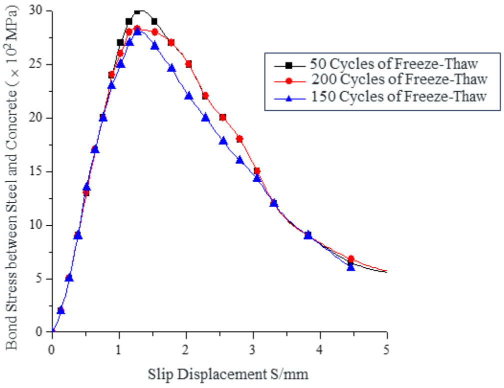
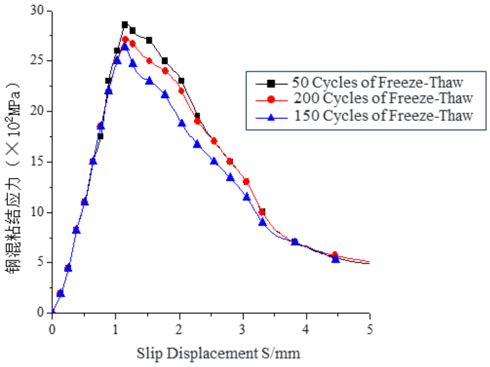


Fig. 18 – Bond-slip curve after 150 freeze-thaw cycles

Fig. 19 – Bond-slip curve of specimen in water



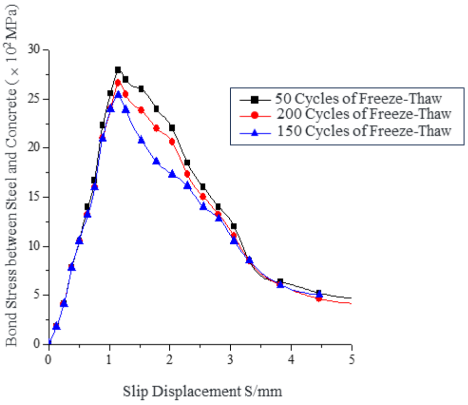


Fig. 20 – Bond-slip curve of specimen in NaCl solution

Fig. 21 – Bond-slip curve of specimen in solution A

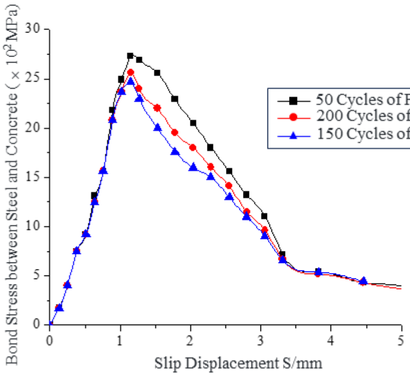


Fig. 22 – Bond-slip curve of specimen in solution B

From Figure 16, it can be observed that after 50 freeze-thaw cycles, the maximum bond stress between steel and concrete for each group of specimens has decreased to some extent. Compared to the data obtained from the control specimens, the specimens immersed in Solution B experienced a decrease of 15.9%, those in Solution A decreased by 13.8%, in NaCl solution decreased by 11.9%, and in water decreased by 7.6%. The decrease in the maximum bond stress for the specimens immersed in Solution B is more than twice that of water, indicating a significant detrimental effect of Cl- on the bond strength between steel and concrete.

From Figure 17, it can be observed that after 100 freeze-thaw cycles, there is a significant decrease in the maximum bond stress between steel and concrete for each group of specimens. Compared to the data obtained from the control specimens, the specimens immersed in Solution B experienced a decrease of 21.0%, those in Solution A decreased by 17.8%, in NaCl solution decreased by 16.4%, and in water decreased by 12.8%. Compared to the specimens after 50 freeze-thaw cycles, the maximum bond stress for the specimens immersed in water, NaCl solution, Solution A, and Solution B decreased by 5.2, 4.5, 4, and 5.1 percentage points, respectively.

From Figure 18, it can be observed that after 150 freeze-thaw cycles, there is a more significant decrease in the maximum bond stress between steel and concrete for each group of specimens. Compared to the data obtained from the control specimens, the specimens immersed in Solution B experienced a decrease of 23.9%, those in Solution A decreased by 21.6%, in NaCl solution decreased by 18.7%, and in water decreased by 13.7%. Compared to the specimens after 100 freeze-thaw cycles, the maximum bond stress for the specimens immersed in water, NaCl solution, Solution A, and Solution B decreased by 0.9, 2.3, 3.8, and 2.9 percentage points, respectively.

From Figure 19 – Figure 22, it can be observed that with the same immersion liquid, the more freeze-thaw cycles, the smaller the maximum bond stress and residual bond stress of the reinforced concrete specimens. Compared to 50 freeze-thaw cycles, after 150 freeze-thaw cycles, the maximum bond stress and residual bond stress of the specimens immersed in water decreased by 5.6% and 9.3% respectively; in NaCl solution, the maximum bond stress and residual bond stress decreased by 7.6% and 7.5% respectively; in Solution A, the maximum bond stress and residual bond stress decreased by 9.2% and 7.9% respectively; in Solution B, the maximum bond stress and residual bond stress decreased by 9.5% and 8.1% respectively.

It is evident that the more freeze-thaw cycles and the higher the Cl- concentration, the more severe the damage to the bond stress between steel and concrete. Therefore, it is possible to suppress the damage to the bond stress by reducing the Cl- content in the reinforced concrete structures through methods such as electrochemical chloride extraction. This will enhance the durability and service life of the structures.

Freeze-thaw damage not only affects the maximum bond stress of reinforced concrete, but also reduces the residual bond stress to some extent. Figure 23 – Figure 25 show the residual bond stress diagrams after pull-out tests for each specimen, which visually reflect the effects of different freeze-thaw cycles and solutions on residual bond stress.

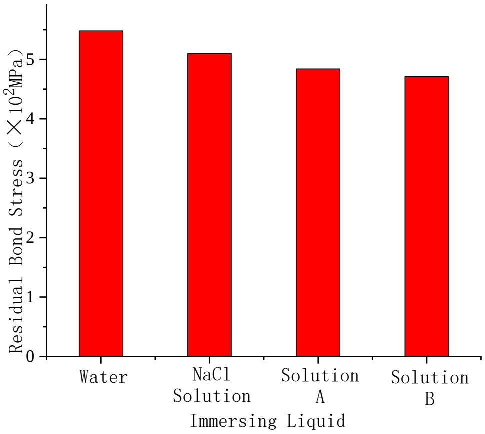


Fig. 23 – Residual bonding stress of specimen after 50 freeze-thaw cycles

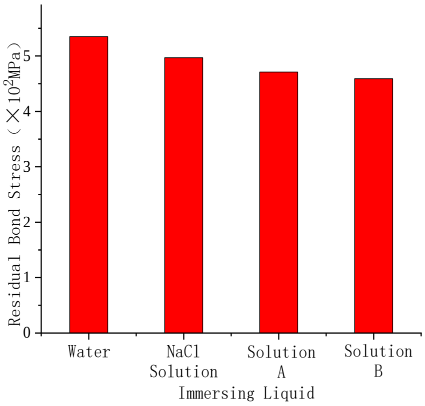


Fig. 24 – Residual bonding stress of specimen after 100 freeze-thaw cycles

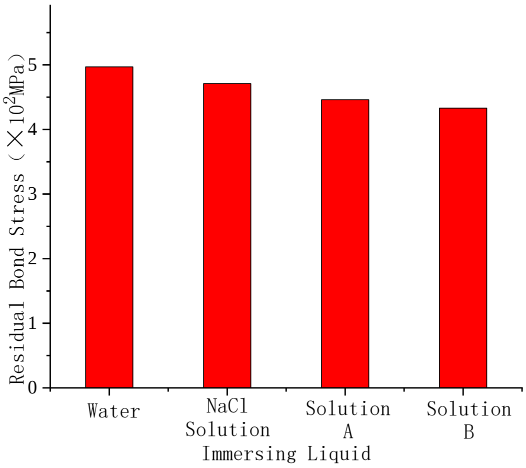


Fig. 25 – Residual bonding stress of specimen after 150 freeze-thaw cycles

It can be observed that for the same number of freeze-thaw cycles, the specimens immersed in water have the highest residual bonding stress, while the higher the Cl- concentration in the immersed solution, the lower the residual bonding stress. After 50 freeze-thaw cycles, the residual bonding stress of the specimens in water is 1.2 times that of those in Solution B. After 100 freeze-thaw cycles, it is still 1.2 times, and after 150 freeze-thaw cycles, it is 1.1 times.

When the liquid for immersion is the same, the higher the number of freeze-thaw cycles, the lower the residual bonding stress, indicating that freeze-thaw cycles have a significant impact on the bonding stress and residual bonding stress of steel-concrete. This greatly reduces the durability of the structure. The specific effects are shown in Figure 26 – Figure 29.

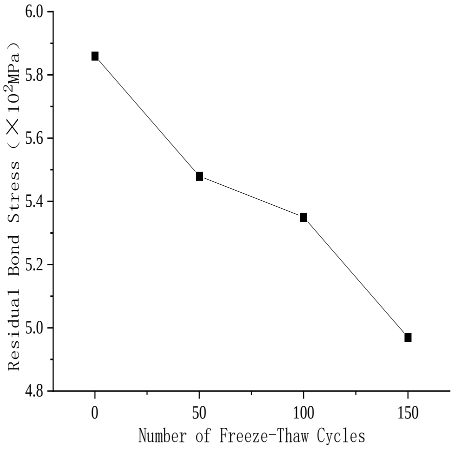


Fig. 26 – Residual bonding stress of specimen in water

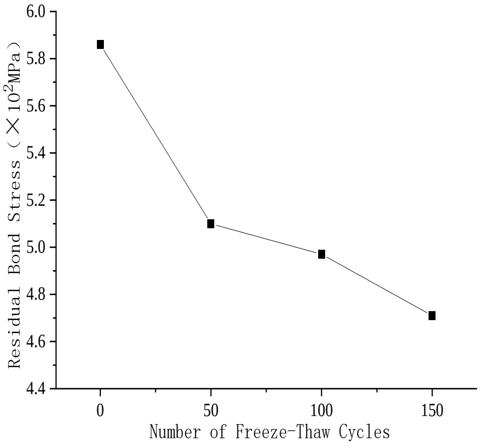


Fig. 27 – Residual bonding stress of specimen in NaCl solution

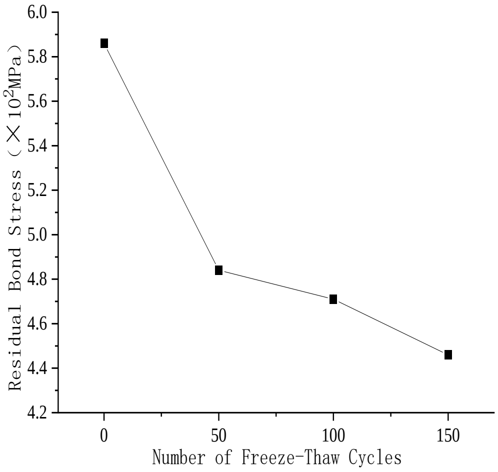


Fig. 28 – Residual bonding stress of specimen in solution A

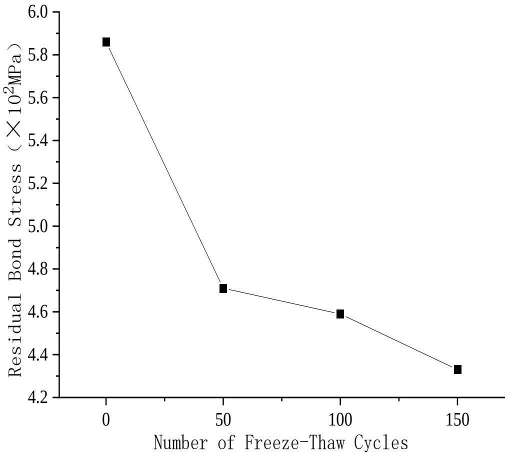


Fig. 29 – Residual bonding stress of specimen in solution B

The loss curve of residual bond stress in chloride ion solutions has a steeper slope compared to water, and the decreasing trend becomes more pronounced with increasing concentration. For road, bridge, and marine engineering projects that utilize reinforced concrete in cold regions, measures can be taken to improve the quality of concrete (such as using water-reducing agents, composite materials, etc.) to enhance its frost resistance, impermeability, and prevent freeze-thaw erosion. Additionally, physical and chemical methods can be employed to reduce the Cl- content both internally and externally in the structure, thereby preventing Cl- corrosion damage.

CONCLUSION

The comprehensive performance of concrete in bridge deck structures after salt freezing was studied, focusing on the dynamic elastic modulus of reinforced concrete and the bond performance between steel and concrete. The experimental data for the dynamic elastic modulus were analyzed using Matlab software to obtain mathematical expressions for the variation curves of concrete specimens under different freeze-thaw conditions. A pull-out test was performed to measure parameters such as pull-out force and residual bond stress, and to plot the load-slip curve, aiming to investigate the changes in bond performance of reinforced concrete after salt freezing. The following conclusions were drawn:

(1) Chloride ions of a certain concentration can inhibit the attenuation of dynamic elastic modulus in bridge deck concrete to a certain extent. There exists a critical Cl- concentration value that provides the strongest inhibitory effect and leads to minimal loss of dynamic elastic modulus.

(2) With an increase in freeze-thaw cycles, the relative dynamic elastic modulus of water specimens was significantly lower than that of specimens in other solutions. Analysis with Matlab software revealed that the relative dynamic elastic modulus of water specimens reached 59.6% after 316 freeze-thaw cycles, exceeding the failure limit.

(3) The bond strength between steel and concrete in bridge deck structures was visibly affected in the presence of chloride ions, with a stronger destructive effect observed at higher ion concentrations and after more freeze-thaw cycles. After 150 freeze-thaw cycles, compared to the control specimen, the specimens in Solution B decreased by 23.9%, Solution A decreased by 21.6%, NaCl solution decreased by 18.7%, and water decreased by 13.7%.

(4) The salt freezing environment significantly affects the bond stress and residual bond stress between steel and concrete in bridge deck structures, greatly reducing the durability of the structure. In order to increase the durability of the concrete bridge deck, it is necessary to ensure the integrity of the bridge deck pavement and avoid rain erosion of the reinforced concrete bridge panel.

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