Bond Slip Law and Micropore Structure of Freeze-thaw Concrete

Anqi Wang¹ and Xiaolin Yang*¹

¹School of Civil engineering, Qinghai University, Xining, Qinghai, 810016, P.R. China
*672092726@qq.com

Abstract. In order to study the influence of freeze-thaw cycles on the bond-slip relationship between concrete and steel bars, uniaxial compression and pull-out tests were carried out on concrete cubes experiencing 0, 25, 50 and 75 freeze-thaw cycles according to the existing stress models and the related concepts of ultimate bond force after freeze-thaw cycles. The bond stress and slip law between freeze-thaw concrete and steel bar are obtained. At the same time, the bond slip curve can be fitted by Bigaussian function. The results showed that with the increase of freeze-thaw times, the micro-pore structure on the surface and inside of concrete expands, the uniaxial compressive strength decreases, and the bond stress and slip between steel bar and concrete decrease.

1. Introduction
Nowadays, modern buildings are mainly reinforced concrete structures. Through the understanding of reinforced concrete structures, the conditions to ensure that concrete and reinforcement can work well are good bonding performance between concrete and reinforcement, similar linear expansion coefficient of temperature between them and the protective effect of concrete on internal reinforcement. The bonding force between steel bar and concrete consists of three parts: the chemical bonding force produced by cement cementitious body in concrete on the surface of steel bar, the frictional resistance of surrounding concrete to steel bar and the mechanical bonding force between deformed steel bar ribs and concrete. In most areas of northern China, reinforced concrete buildings will be damaged by freeze-thaw due to cold weather. During the freeze-thaw cycle, the bond strength between reinforcement and concrete will degrade after freeze-thaw cycle, which will damage the working conditions of reinforced concrete.

At present, it is generally acknowledged that the mechanism of bond behavior between steel bar and concrete was proposed by R. M. Mains in the 1950s. The stress distribution of round bars and deformed bars obtained by grooving and embedding strain gauges inside the bars is presented. The bond between the bars and concrete is mainly composed of chemical bonding force, friction force and mechanical biting force [1]. There are many studies on bond-slip behavior of reinforced concrete. The existing bond test methods [2] include center pull-out test, beam-end pull-out test and local bond-slip test. Thompson [3] obtained that the bonding force is proportional to the square of concrete strength by experiment. Wang Qian [4] carried out pull-out tests by placing strain gauges in the grooves of reinforcing bars. It was found that the bond strength between reinforcing bars and fly ash increased with the decrease of the diameter of reinforcing bars. In this paper, the central pull-out test of reinforced concrete specimens is carried out, and the effect of freeze-thaw cycles on the bond properties between reinforced concrete is studied. The τ-s curve under freeze-thaw cycles is obtained,
and is fitted with the empirical formula studied by predecessors. The results show that Bigaussian function has a higher degree of fitting.

2. Experimental work

2.1. Experimental design and process
In order to study the bond-slip behavior between steel bars and concrete after freeze-thaw, 48 cubic concrete blocks (effective anchorage length \( L = 6 \text{cm} \)) of 100mm *100mm *100mm were fabricated by standard method (GB/T50152-2012). Cement is P.O.42.5. The diameter of the reinforcement is 12mm and its strength grade is HRB300. The test block is poured with standard mould and vibrated on the vibration table. The molds shall be removed after 24 hours and maintained in the standard curing room for 28d. Then the block was divided into four conditions for freeze-thaw. The mass ratio of cement, water, sand and gravel used in the test is 1:0.5 1.65:3.34. Freezing and thawing cycles of 0, 25, 50 and 75 times were carried out for the separated concrete specimens. The freeze-thaw cycle test of reinforced concrete adopts the quick freezing method standard in the "test method for long-term performance and durability of ordinary concrete" (GB/t50082-2009).

As a common method to study the bond-slip law of reinforced concrete, the central pull-out test is also used in this experiment \[^5\]. The test is completed by a computer-controlled electro-hydraulic servo universal testing machine. Experimental data were collected by computer and load and slip curves were drawn.

2.2. Experiment on concrete compression after freeze-thaw
In order to meet the needs of the following fitting experiments, the compressive strength test of freeze-thaw concrete was carried out at the same time as the tensile test of freeze-thaw concrete. Through the compressive strength test, it is found that the compressive strength of concrete decreases with the increase of freeze-thaw times, which may be caused by a large number of pore in concrete after expansion. The compressive strength of concrete revised according to the code is 0.95 times of the measured value. The concrete compressive strength is shown in Table 1. The failure curve under compression is shown in Figure 1.

| Freeze-thaw cycles | 0    | 25   | 50   | 75   |
|-------------------|------|------|------|------|
| \( f_{cm}/\text{Mpa} \) | 44.53| 38.30| 32.95| 12.32|

Table 1. Concrete of C35 crushing strength.

![Figure 1. Compressive strength curve of C35 freeze-thaw concrete.](image)
3. Macroscopic and microscopic characteristics of freeze-thaw concrete

3.1. Macroscopic failure characteristics of freeze-thaw concrete

The macroscopic deformation of concrete due to temperature is clearly visible. Concrete peeling occurred on the surface of the specimen, and the peeling degree increased with the increase of freeze-thaw times. There are pits of different sizes on the surface of concrete after the mortar peeling, accompanied by the peeling of stones and the exposure of coarse aggregates. This phenomenon is particularly evident in concrete that has experienced 50, 75 freeze-thaw cycles. When the volume of concrete expands to a certain extent after freeze-thaw, the concrete will crack, which leads to the reduction of the binding force of concrete on steel bars and the failure of bonding. The degree of concrete expansion varies with the number of freeze-thaw cycles. With the continuous expansion, concrete cracks will appear to varying degrees until they crack. In the tension test of freeze-thaw concrete, the concrete with more freeze-thaw cycles will split directly, while the concrete with less freeze-thaw cycles will slip. The specimen after bonding failure is shown in figure 2.

![Specimen shape after bond failure.](image)

3.2. Microstructure characteristics of freeze-thaw concrete

The distribution of cracks on concrete surface was observed by ZBL-130 crack width observer after freezing-thawing 0, 25, 50 and 75 times. The surface morphology of concrete was observed under a 50-fold mirror, and the crack microporosity was analyzed by PCAS system \(^6\), \(^7\). The PCAS used in this paper is developed by Nanjing University. Its main functions are automatic recognition, geometric quantification and statistical analysis of grain, pore and fracture images. Compared with traditional manual measurement, PCAS system has the advantages of automation and repeatability. The system has been used in the fields of quantitative identification and structural analysis of rock and soil fissures, shale gas voids and mineral particles, as well as in the fields of materials and biology. PCAS research found that the surface of concrete without freeze-thaw is smooth and almost no holes can be seen, and the crack microporosity is 0.06%. The microporosity of concrete surface cracks in 25 cycles is 1.65%. The microporosity of concrete surface cracks in 50 cycles is 1.76%. The microporosity of concrete surface cracks in 75 cycles is 2.92%. Therefore, with the increase of freeze-thaw cycles, the microporosity of cracks on concrete surface is also increasing. The specific morphology and distribution status are shown in figure 3, and the fracture microporosity is shown in table 2.

![Microstructure characteristics of freeze-thaw concrete](image)
4. Results and discussion

4.1. Law of bond slip after freeze-thaw

In this paper, the most widely used threaded steel in practical engineering is used as experimental material. The existing research results show that the bonding force of threaded steel mainly consists of chemical adhesive force, friction force and mechanical biting force. And the mechanical occlusion force is especially important in the threaded steel bar. The main reason for the change of bond force between concrete and steel bar after freeze-thaw cycles is the change of chemical bond force. In the freeze-thaw cycle experiment, it is found that the degree of expansion of concrete experienced different freeze-thaw cycles is different. Through the central pull-out test, it is found that different freeze-thaw times of concrete have different bonding degree to steel bar. When processing the experimental data, it is considered that the bond stress between steel bar and concrete distributes uniformly along the whole bond length. The average bond stress is defined as follows:

Table 2. Microporosity of concrete surface.

| Freeze-thaw cycles | 0   | 25  | 50  | 75  |
|--------------------|-----|-----|-----|-----|
| Fracture porosity  | 0.06| 1.65| 1.76| 2.92|

Using JSM-6610LV scanning electron microscope to observe and analyze the internal characteristics of freeze-thaw concrete after 500 times magnification. It was found that with the increase of freeze-thaw cycles, the amount of silicon dioxide (white matter in figure 4) precipitation also increased, as shown in figure 4.
\( \tau = \frac{P}{\pi d l} \)  

(1)

\( \tau \) is the average stress. The unit is MPa.  
\( P \) is the peak tension of the reinforcement. The unit is N.  
\( L \) is the bond length between steel and concrete. The unit is mm.  
\( D \) is the diameter of the reinforcement. The unit is mm.

In this experiment, the bonding length between all reinforcement and concrete is 60mm, and the diameter of reinforcement is 12mm.

The bonding slip curve was obtained by collating the experimental data of tensile displacement obtained by the testing machine. It can also be clearly seen from the experimental results that the maximum peak stress and corresponding slip amount of concrete without freeze-thaw are the largest. The higher the number of freeze-thaw cycles, the smaller the peak stress and the smaller the slip. After reaching the peak stress, the stress curve drops abruptly and the bond is destroyed. The bond slip curve is shown in figure 5. Compared with the results of Niu Jiangang’s literature [8], it is found that the ultimate bond stress and slip values in this paper are close to those in the same freeze-thaw cycles, and the minor differences may be caused by different labels and mix ratios.

4.2. Experimental data fitting

Scholars from various countries have done a lot of research on the bond slip relationship between reinforcement and concrete under monotonic loading. But there is still a lack of a complete theoretical system for the influence of freeze-thaw factors.

Nilson [9] sorted out Bresler’s experimental results and proposed a bonding slip relation expressed by cubic polynomial, as follows:

\[ \tau = 9.81 \times 10^2 s - 5.74 \times 10^4 s^2 + 0.837 \times 10^6 s^3 \]  

(2)

\( \tau \) is the bond stress. The unit is N/mm².  
\( s \) is the relative slip. The unit is mm.

Houde [14] presents an empirical formula of quadratic polynomial based on the tensile tests of steel bars with three different diameters, as follows:

\[ \tau = (5.30 \times 10^2 s - 2.52 \times 10^4 s^2 + 5.87 \times 10^5 s^3 - 5.47 \times 10^6 s^4) \sqrt[40.7]{\frac{f_c}{fc}} \]  

(3)

\( \tau \) is the bond stress. The unit is N/mm².  
\( s \) is the relative slip. The unit is mm.  
\( f_c \) is the compressive strength of concrete. The unit is N/mm².
In this paper, when fitting the above empirical formula of freeze-thaw concrete, it is found that the fitting degree of piecewise gaussian exponent formula is very high. The three fitting curves of concrete with different freeze-thaw cycles are shown in figure 6. It can be found that the difference between the peak stress and the original stress of the curve fitted by Bigaussian is the smallest, which is of more practical significance and has better accuracy in comparison. The fitting formula of Bigaussian is as follows:

\[
\tau = \begin{cases} 
A + Be^{-(s-C)^2/(2 \times D^2)} & (if \ s < C) \\
A + Be^{-(s-C)^2/(2 \times E^2)} & (if \ s > C) 
\end{cases} 
\]  

(4)

In the formula, A, B, C, D and E are the corresponding coefficients when the concrete is freeze-thaw n times. The specific values are shown in table 3.

Table 3. The related coefficients in the piecewise gaussian function fitting formula.

| Freeze-thaw cycles | 0    | 25   | 50   | 75   |
|--------------------|------|------|------|------|
| A                  | 1.7822 | 1.7463 | 2.0751 | 1.4644 |
| B                  | 17.5844 | 14.6978 | 11.6147 | 7.0700 |
| C                  | 2.3134 | 1.8655 | 1.4404 | 1.0591 |
| D                  | 0.7402 | 0.5421 | 0.4076 | 0.3543 |
| E                  | 0.0001 | 0.0002 | 0.1431 | 0.2239 |

Figure 6. Fitting curve.
(The solid black line is the original curve. The dotted red line is a cubic curve. The dotted blue line is a quartic curve. Green is the Bigaussian curve.)
5. Conclusion
1. The results show that with the increase of freeze-thaw times, the surface and internal micropore structure of concrete expands, the uniaxial compression strength decreases, and the bond stress and slip between steel and concrete decrease.

2. From the failure photos of concrete, it can be seen that the adhesive slip failure is not the crushed aggregate, but the hydrated cement slurry and the transition phase with the aggregate.

3. According to the fitting curve, the Bigaussian function can be used to fit the bond slip of freeze-thaw concrete, and the stress value at the failure can be well fitted.

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