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# Analysis on effects of freeze-thaw cycle on mechanical properties of concrete

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**ABSTRACT**

*This paper made an experimental study on the attenuation law of basic mechanical properties of concrete after the action of freeze-thaw cycle, and constructed a mathematical model of complete compressive stress-strain curve equation of concrete. Based on the test data, compressive stress-strain relation of concrete after the action of freeze-thaw cycle was gained. Besides, a comparison was made between experimental value and theoretical value of compressive stress-strain relation of concrete after freeze-thaw, which verified the accuracy of the established mathematical model. By studying the attenuation law of anti-frost property and mechanical properties of concrete, its change rule was revealed. This has provided basic data for theories of frost resistance durability design for concrete structure in practical engineering.*

**Keywords**: concrete; freeze-thaw cycle; mathematical model; mechanical property

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## INTRODUCTION

Since concrete was applied to engineering construction, the improvement and enhancement for concrete properties has been perfected gradually with the increase of engineering practice and development of science and technology. With development of technology, people have realized that not all the existing concrete work is durable. The lifetime is far lower than the design and the concrete work is damaged early; these are all problems that happen frequently. Huge reconstruction, reinforcement and maintenance costs are required for these projects that age early; besides, great economic losses and potential risk will be caused. Some experts name this phenomenon as concrete durability crisis[1]. Freeze-thaw is one of the major reasons that result in premature senility of concrete work; frost resistance is also one of the important indexes for durability of concrete. Frost resistance durability of concrete will affect the service life and property of concrete; moreover, freeze injury of concrete can appear in a large area. In China, most places are located in severe cold, and phenomenon of freeze-thaw damage happens to most concrete hydraulic structures. The major disease during the operation process is freeze-thaw damage of concrete structure or buildings in projects like irrigation works, harbor works, road, and bridge in cold region under the effects of freeze-thaw cycle.

## 2. Mechanism of freeze-thaw damage

The freeze-thaw damage process of concrete is a complicated physical change process. The damage of freeze-thaw cycle to concrete is the result of combined action of water expansion pressure caused by volume expansion when water turns into ice under a certain freezing temperature and seepage pressure caused by vapor pressure difference of ice and water. At a certain negative temperature, pore water in concrete will present state transformation and the volume can expand by 9% when water transforms into ice. Expansion pressure will be generated under the restriction of pore wall, thus pulling stress will be produced in the microstructure around the pore. Such damage brought about by expansion pressure caused by water volume expansion at negative temperature mainly depends on the existence form of water in concrete, its internal micro-pore structure, and outside temperature change[2]. Seepage pressure is caused by the two-phase free energy difference between ice and water in the pore. Under a certain temperature, free energy of ice is smaller than free energy of liquid water. During freeze, water in the gel pore flows toward the pore; when water arrives in the pore, freeze will be caused, and volume of ice will increase. When water in the pore is frozen, supercooled water in the gel pore migrates and redistributes in the microstructure of concrete, which might result in seepage pressure; thereby, the freezing point of water in pore of the concrete drops with the decrease of pore diameter due to the effects of surface tension. When water in macropore is frozen, water in the gel pore is not frozen and it is in a supercooled state. At this time, vapor pressure of supercooled water is greater than vapor pressure of ice, which will give rise to water migration and seepage pressure. Migration and permeation of supercooled water will inevitably increase the volume of ice in pore. As a result, a greater pressure will be formed, and microstructure of concrete might be further damaged. If concrete is always in such freeze-thaw cycle, the damage will be accumulated and expanded gradually, which will increase pores in the concrete and connect them together. In this way, denudation from the outside to the inside will happen to the concrete, and the concrete will be further destroyed[3]. In conclusion, as for the freezing damage of concrete, volume of water in the concrete will expand during freeze, which might cause hydrostatic pressure, seepage pressure and water migration, thus structural damage is promoted; it is the damage caused by water movement to the concrete structure.

Factors of affecting freeze-thaw damage can be divided into several categories. Internal factor includes aggregate, cement, additive, water cement ratio, and gas content; it means the quality of the concrete. External factor covers freeze-thaw temperature, freeze-thaw velocity, and imposed load; it is the environmental conditions that will influence concrete. Construction factor involves mix proportion and curing condition. These factors are correlated to each other and also restrict each other; they decide the degree and velocity of freeze-thaw damage to the concrete together[4]. Under the same number of freeze-thaw cycles, the higher the gas content is and the lower the water cement ratio is, the smaller the strength loss of concrete will be. The order of mechanical property loss from big to small is: loss of rupture strength and splitting tensile strength, loss of dynamic modulus of elasticity, and loss of compressive strength. Strength loss of concrete is related to freeze-thaw medium and water cement ratio to some degree. Under the same freeze-thaw damage, the loss of rupture strength will be great when water cement ratio of concrete is high or the freeze-thaw medium is saline solution.

However, previous studies mainly concentrate on the influence of freeze-thaw action on material properties of concrete, and there are few researches on the degradation law of concrete mechanical properties with freeze-thaw action[5]. By constructing mathematical model, this paper launched an experimental study on the degradation law of concrete mechanical properties after freeze-thaw action, trying to explore the working mechanism of concrete material under freeze-thaw environment and to provide basic data for establishing corresponding calculation patterns.

**3. Constructing mathematical model of complete compressive stress-strain curve equation of concrete**

3.1 Compressive deformation and destruction process of concrete test block decide the shape of its complete stress-strain curve. Fig. 1 presents a typical curve chart, and the figure adopts dimensionless coordinates: $y=\sigma/f_{pr}$; $x=\varepsilon/\varepsilon_{pr}$.

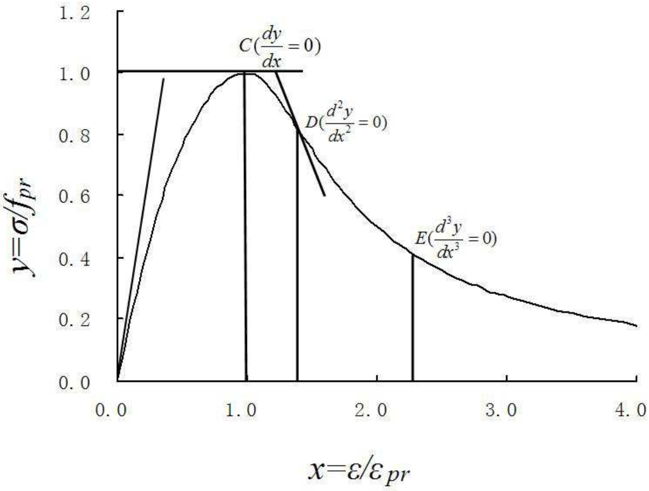


**Fig. 1 Typical complete compressive stress-strain curve**

Geometric characteristics of this typical curve can be described in the following way:

① $x=0, y=0$;

② $0\leq x<1, d^2y/dx^2<0$, rising curve; $dy/dx$, monotone decreasing, without inflection point;

③ When $x=1$, $dy/dx=0$, $y=1$, single-peak curve;

④ At $d^2y/dx^2=0$, coordinate of $Dx>0$; there is an inflection point at $dy/dx$ on the decline curve;
⑤ At $d^3y/dx^3=0$, the coordinate of $De$ ($\geq Dx$) is the coordinate of the maximum curvature point on the decline curve;
⑥ When $x\to\infty$, $y\to 0$, $dy/dx\to 0$;
⑦ $x\geq 0, 0\leq y\leq 1$。

Where coordinate of the peak point is the prismoid strength $f_{pt}$ of concrete and the corresponding peak strain $\varepsilon_{pr}$; the inflection point $D$ on the decline curve is corresponding to appearance of the first visible fissure; the maximum curvature point $E$ is corresponding to the state in which the critical diagonal crack runs through the total cross-section of the test block[6].

It is difficult to choose a single curve equation that can both satisfy all the above geometrical conditions and adjust the accurate curve shape by directing at different types of concrete. However, it is easy to meet the requirements by adopting different equations to satisfy the continuity condition at peak point according to the curve shape in the rising section and decline section.

3.2.1 The simplest form of the curve in rising section ($x\leq 1$) that meets conditions in ①, ②, ③, and ⑦ is cubic parabola

$$\boldsymbol{y=a_0+a_1x^2+a_2x^2+a_3x^3}$$

By substituting the three boundary conditions (***x=0, y=0; x=1, y=1; x=1, dy/dx=0***), we gain: $\boldsymbol{a_0=0;\ a_2=3-2a;\ a_3=a-2}$, which means

$$\boldsymbol{y=ax+(3-2a)x^2+(a-2)x^3} \qquad \text{Formula 1}$$

When $x=0$, $dy/dx=a$; in another word:

$$a=\frac{dy}{dx}\Big|_{x=0}=\frac{d\sigma/f_{pr}}{d\varepsilon/\varepsilon_{pr}}\Big|_{x=0}=\frac{d\sigma/d\varepsilon\big|_{x=0}}{f_{pr}/\varepsilon_{pr}}=\frac{E_0}{E_p}$$

In the formula, $E_0=d\sigma/d\varepsilon\big|_{x=0}$ – initial tangent modulus of elasticity of concrete, $N/mm^2$;
$E_p=f_{pr}/\varepsilon_{pr}$ – peak secant modulus of concrete, $N/mm^2$;

$a$ is the ratio between initial tangent modulus and peak secant modulus.

According to the condition in ②, when $0\leq x<1$, $d^2y/dx^2=2(3-2a)+6(a-2)x<0$

The range of $a$ is gained: $1.5\leq a\leq 3$

3.2.2 Curve in decline section ($x\geq 1$), the form that meets the requirements is rational fraction

$$y=\frac{x}{bx^2+b_1x+b_2} \qquad \text{Formula 2}$$

By substituting $x=1, y=1$; $dy/dx=0$ into Formula 2, we obtain $b_1=1-2b$; $b_2=b$;

Then we gain:

$$y=\frac{x}{b(1-x)^2+x} \qquad \text{Formula 3}$$

When $b=0$, $y=1$; Formula 3 is a horizontal line extending from the peak point, equivalent to ideal plastic deformation;

When $b\to\infty$, $y=0$; residual strength of material after the peak point is zero, equivalent to completely brittle material. Therefore, the value range of $b$ is: $0<b<\infty$

According to Condition 4, it meets

$$\frac{d^2y}{dx^2}=\frac{2b^2[x^3-3x+(2-\frac{1}{b})]}{[b(x-1)^2+x]^3}=0 \quad \text{Formula 4}$$

According to Formula 4, the inflection point D is corresponding to the coordinate for appearance of the first visible fissure.

Similarly, according to conditions in 3.1.5, it meets

$$\frac{d^3y}{dx^3}=\frac{-6b[b^2x^4-6b^2x^2+(8b^2-4b)x-(3b^2-4b+1)]}{[b(x^2-1+x)]^3}=0 \quad \text{Formula 5}$$

According to Formula 5, the coordinate of the maximum curvature point *E* that is corresponding to the state in which the critical diagonal crack runs through the total cross-section of the test block can be obtained. In this way, the mathematical model of complete compressive stress-strain curve equation of concrete is constructed.

4. Compressive stress-strain relation of concrete after freeze-thaw action
4.1 Overview about the test
The test process involves 4 links which are preparation of concrete test block, rapid freeze-thaw test, scanning electron microscopy test, and uniaxial compression test.

4.1.1 Design of test block
In order to study the change rule of compressive stress-strain relation of concrete after action of different freeze-thaw cycles, 6 groups, with 3 blocks in each group, were prepared. Size of the concrete prismoid test block is 100*100*400mm. Rapid freeze-thaw cycle test was conducted for them respectively, *n*=0 time, 100 times, 150 times, 200 times, 250 times, and 300 times. Number of the corresponding test block groups is C1, C2, C3, C4, C5, and C6. Besides, 4 additional groups were prepared, with 3 blocks in each group. The cubic test blocks of 100*100*100mm were used to measure compressive strength of concrete cube and conduct scanning electron microscopy observation test.

4.1.2 Raw materials of test block and preparation
See Table 1 for mix proportion of concrete, in which the water-binder ratio and sand ratio are 0.37 and 0.39 respectively. Early strength ordinary portland cement produced by Shandong Sunnsy Cement Plant was adopted (P.O 42.5R), and a few silica fumes and coal ashes were mixed with it to improve the internal microstructure. Appropriate superplasticizer was added during the preparation process, so as to effectively guarantee high workability of the newly mixed concrete; 0.02% air entraining agent was added, to make the actually measured gas content in the newly mixed concrete reach 5.8%, which could guarantee good anti-frost property of concrete. After 28 days, compressive strength of the concrete cube was 50MPa, which verified that the prepared concrete reached the strength standard of high-property concrete.

**Table 1 Mix proportion of concrete**

| Water-binder ratio | Binding material /$kg\cdot m^{-3}$ | | | Water | Sand | Macadam |
|---|---|---|---|---|---|---|
| | Cement | Coal ash | Silica fume | $kg\cdot m^{-3}$ | $kg\cdot m^{-3}$ | $kg\cdot m^{-3}$ |
| 0.38 | 325 | 30 | 15 | 140 | 745 | 1160 |

4.1.3 Test process
Freeze-thaw cycle was conducted for the above groups of test block for 0 times, 100 times, 150 times, 200 times, 250 times, and 300 times. In each group, freeze-thaw test was carried out for prismoid test block accompanied by a cubic test block of 100*100*100mm. After the set freeze-thaw cycles were completed, sampling was conducted in the cubic test block for scanning electron microscope observation. Finally, uniaxial compression test was conducted for test blocks in each group after freeze-thaw action, and stress-strain test curve was gained.

4.1.4 Test measurement
During the process of rapid freeze-thaw test, horizontal base frequency measurement was conducted for the test block in each group every 50 freeze-thaw cycles, so as to gain the corresponding dynamic modulus of elasticity through calculation. Besides, external damage of the test block was checked, and its weight change was recorded. Moreover, the measurement was continued till the decline section of complete stress-strain test curve of concrete. In order to measure the decline section of complete stress-strain test curve of concrete, additional rigid element was

attached to the testing machine; when strain of the test block reached the peak value, rigid element would help to absorb strain energy rapidly released by the testing machine, so as to prevent the test block from being squashed instantly. Therefore, a complete stress-strain test curve was gained.

4.2 Test phenomenon

With the increase of freeze-thaw cycle number, the damage situation on the test block surface could be observed with the naked eye. Firstly, the originally smooth cement mortar surface became rough gradually, and fine aggregate was exposed. Then some surfaces dropped off till the entire surface layer peeled off. Finally coarse aggregate was exposed and some edge dropped off. By observing the accompanying test blocks with scanning electron microscope, we clearly saw the process of damage to the internal microstructure of concrete caused by freeze-thaw action. Internal pores in the test block not experiencing freeze-thaw had a proper pore diameter and even distribution. After freeze-thaw cycle for 300 times, obvious net-shaped fractures appeared among the pores. In uniaxial compression test, with gradual increase of test load, the test block experienced several stages like elastic deformation, fissure appearance, fissure development, and test block damage. By cutting the broken test block open, we found that the damage parts mainly distributed along the interfacial transition zone of set cement and aggregate as well as in the set cement; the coarse aggregate was not destroyed.

4.3 Test results and analysis

4.3.1 Freeze-thaw property parameter

With the increase of freeze-thaw cycle number, loss ratio of weight and loss ratio of relative dynamic modulus of elasticity also increase. Non-damage detection can be realized more easily for loss ratio of relative dynamic modulus of elasticity and it is more sensitive to internal structure damage of concrete. Therefore, it was selected as the freeze-thaw property parameter for mechanical property analysis. By conducting regression analysis on loss ratio of relative dynamic modulus of elasticity after freeze-thaw cycle for the set times, the relation curve between loss ratio of relative dynamic modulus of elasticity and freeze-thaw cycle number was obtained via fitting, as shown in Fig. 2 and Formula (6). The fitting formula curve matches the test value well.

$$\Delta E_n = -3.57 + 0.50e^{\frac{n}{122}}$$ Formula 6[7]

In the formula, $\Delta E_n = \frac{E_0 - E_n}{E_0} = \frac{f_0^2 - f_n^2}{f_0^2} * 100\%$ is the loss ratio of relative dynamic modulus of elasticity (%) after freeze-thaw cycle for *n* times; where $E_n$ and $E_0$ are elasticity modulus of concrete not experiencing freeze-thaw and concrete after freeze-thaw action for *n* times, and $f_n$ and $f_0$ are horizontal base frequency (*Hz*) of the concrete test block not experiencing freeze-thaw and test block after freeze-thaw action for *n* times.

4.3.2 Mechanical property parameter

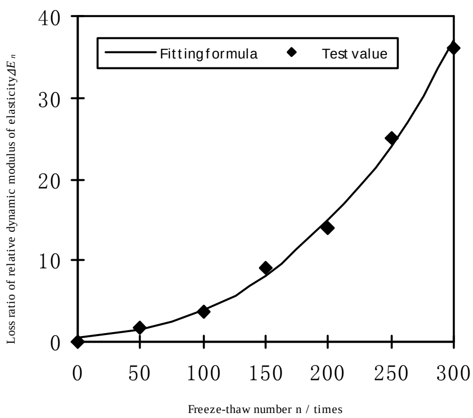


**Fig. 2 Relation curve between loss ratio of relative dynamic modulus of elasticity and freeze-thaw number**

See Table 2 for the test results. According to Table 2, with the increase of freeze-thaw cycle number, elasticity modulus and peak stress both decrease. As for the reason, freeze-thaw action induces minor damage in the internal structure of concrete; besides, with extension of freeze-thaw cycle, the damage is accumulated and expanded; thus internal structure of the test block becomes loose and degenerative. As a result, rigidity and carrying capacity of concrete both decrease. According to test results of this paper, compared with the decay law of monotonic decrease of peak stress, peak strain of test blocks in various groups declines at first and then increases with the increase of freeze-thaw cycle number; mutation happens in C3 and C4. Axial compression peak strain of test blocks in C1 and C2 drop gradually. This shows that the internal damage of freeze-thaw cycle to concrete is at a stage of local occurrence and accumulation; microfractures do not fully extend and connect each other; the microstructure is not loose and still possesses high rigidity, which can be verified by the gentle decrease trend of elasticity modulus of test blocks in C1-C3 groups. When the test block experiences freeze-thaw cycle for more than 100 times, internal damage of concrete enters a development stage; fracture extension happens, the internal structure is obviously loose, rigidity decreases substantially, growth rate of concrete strain becomes higher, and the peak strain obviously increases. Therefore, freeze-thaw cycle for 100 times is the abrupt change point to cause degradation of mechanical properties of concrete. The test results show that transverse deformation coefficient of the test block increases with the rise of load level; the transverse deformation ability of test blocks undergoing more freeze-thaw cycles is smaller under the same stress level among test blocks experiencing freeze-thaw cycle for different times.

**Table 2 Data about test results of complete stress-strain curve**

| No. of test block group | Average value of peak stress (Mp) | Average value of peak strain ($\times10^{-4}$) | Average value of elasticity modulus ($\times10^{4}$MP) |
|---|---|---|---|
| C1 | 43.12 | 18.35 | 3.25 |
| C2 | 35.41 | 16.07 | 3.18 |
| C3 | 32.82 | 15.18 | 3.01 |
| C4 | 31.57 | 16.02 | 2.75 |
| C5 | 29.03 | 20.23 | 1.96 |

4.3.3 Complete stress-strain curve equation of concrete

By referring to the existing research achievements about complete stress-strain curve test of concrete, two mathematical models were built, as shown in Formula 6. It can better reflect the rising section and decline section of stress-strain curve of concrete after freeze-thaw action.

$$y=\begin{cases} ax+(3-2a)x^2+(a-2)x^3 & (x<1) \\ \dfrac{x}{b(x-1)^2+x} & (x\geq 1) \end{cases} \qquad \text{Formula6}$$

$x=\varepsilon/\varepsilon_c$ ; $\varepsilon_c$ and $f_c^*$ are axial compressive strength and the corresponding peak strain of concrete prismoid

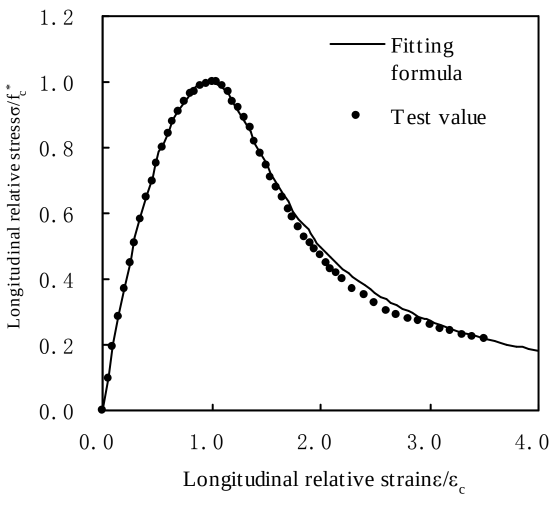


**Fig. 3 Comparison between test value after freeze-thaw cycle for 100 times and fitting stress-strain curve**

According to the test results, with the increase of freeze-thaw cycle number, mechanical properties of concrete decreases, and all these basic mechanical property parameters can be reflected on the complete stress-strain curve of concrete. Therefore, comprehensive consideration should be given to freeze-thaw properties and mechanical properties of concrete, so as to reflect their relation in the relation between loss ratio of relative dynamic modulus of elasticity $\Delta E_n$ and parameter *a* and *b* on stress-strain curve. See Formula 7 and 8 for the relation, and the fitting curve matches the test value well.

$a=-0.0143\Delta E_n+1.744$ Formula 7

$b=0.0796\Delta E_n +1.582$ Formula8[8]

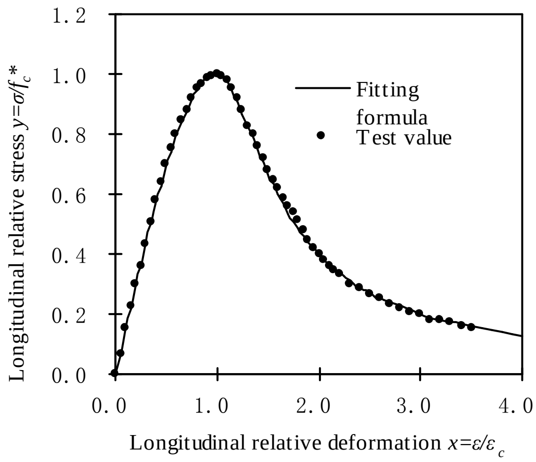


**Fig. 4 Comparison between test value after freeze-thaw cycle for 200 times and fitting stress-strain curve**

## CONCLUSION

By analyzing the above experimental study results, the following conclusions have been gained:

5.1 With the increase of freeze-thaw cycle number, basic mechanical properties of concrete, such as ultimate bearing capacity, transverse deformation coefficient, and elasticity modulus, decrease to varying degrees. Besides, with the increase of decrease degree, safety of structure will be reduced.

5.2 By inducing freeze-thaw property parameter $\Delta E_n$ into the mechanical property parameter *a* and *b*, complete stress-strain curve equation of concrete (Formula 6) has been established, and it matches the test curve well. Thus the relation between compression behavior and freezing-thawing resisting performance of concrete is constructed; meanwhile, accuracy of the established stress-strain curve model of concrete has been verified.

## REFERENCES

[1]SONG Yupu, JI Xiaodong. *Journal of Hydraulic Engineering*, **2006**, (03): 259-263.
[2] TANG Guangpu, LIU Xila, SHI Shisheng. *Chinese Journal of Rock Mechanics and Engineering*, **2006**, 25(12): 2572-2578.
[3] HONG Jinxiang, HUANG Wei, MIAO Changwen, QIN Xiaodong. *Journal of Highway and Transportation Research and Development*, **2006**, 23(7): 14-18.
[4] George W. Scher er. *Cement and Concrete Research*, **2004**, 34: 1613-1624.
[5] LIU Juanhong, SONG Shaomin. *Journal of The Chinese Ceramic Society*, **2005**, 33(4): 528-532.
[6]LI Junyi, LI Xiaoming, XU Caihong. *Port & Waterway Engineering*, **2005**, 11: 5-8.
[7]YANG Quanbing. *Journal of Building Materials*, **2005**, 8(5): 495-498.
[8]JIA Yaodong, XIE Yongjiang, ZHU Changhua. *Concrete*, **2005**, 6: 24-28.