

Uniaxial Dynamic Tensile Properties of Hydraulic Concrete after Freezing-Thawing Cycles

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ABSTRACT: In this paper, freeze-thaw cycles tests of 0, 25, 50, 75 and 100 times for large aggregate concrete were carried out and uniaxial dynamic tensile tests under the strain rates of $10^{-5}/s$, $10^{-4}/s$, $10^{-3}/s$ and $10^{-2}/s$ were also performed. The damage morphology of the specimens after freezing-thawing cycles was observed, the mass loss after different freezing-thawing cycles, the dynamic ultimate tensile strength, peak strain and the relationship of stress-strain under different strain rates were measured. The results showed that relation curve between the mass loss of large aggregate concrete and the freezing-thawing cycles was quadratic. Under the same strain rate, the dynamic ultimate tensile strength and the peak strain decreased with the increase of freezing-thawing cycles. With the same freezing-thawing cycles and the increase of strain rate, the dynamic ultimate tensile strength increased, while the peak strain decreased. According to the test date, the incremental portion of stress-strain curve was fitted and the failure criterion of large aggregate concrete under dynamic uniaxial tensile stress was established, which could provide the theoretical reference for the design and maintenance of large aggregate structures.

KEYWORD: hydraulic concrete; freezing-thawing cycles; dynamic performance; the tensile strength; failure criterion

1 INTRODUCTION

In cold areas all over the world, the hydraulic structures, most of which are made of large aggregate concrete, often suffer from freeze-thaw cycles. Adverse effect on the mechanical properties of large aggregate concrete may caused by freeze-thaw cycles [1-3]. The durability [4-6] is one of the keys for materials which are used in severe environments. At present, the frost resistance of hydraulic structures is measured by the frost resistance of the wet-screened concrete. Wet screening usually results in considerable changes in the composition of materials used in the concrete, especially the proportion of cement mortar and aggregates. However, plenty of large size aggregates containing in the large aggregate concrete may have negative effect on its frost resistance, where the safety design and reliability evaluation of hydraulic structures will be impacted greatly. In addition, dynamic load may also acted on the hydraulic structures inevitably, such as earthquake, wind or wave load, and the mechanical properties of concrete under dynamic and static loads are obviously different. Therefore, it is necessary to investigate the mechanical properties of large aggregate concrete under dynamic load.

Currently, there are some researches on the

mechanical properties of concrete after freeze-thaw cycles all over the world. However, most of the researches focused on wet-screened concrete [7-9] and ordinary concrete [10-13], the frost resistance of large aggregate concrete is rarely studied and the effects of dynamic load are not taken into account either [14-15]. The existing research results show that the compressive strength and tensile strength of both large aggregate concrete and wet-screened concrete decreased significantly with the increase of freezing-thawing cycles, but the reduced value in large aggregate concrete was higher than that in wet-screened concrete, especially the tensile strength. It is reported that [15] the loss rate after 300 freeze-thaw cycles of the uniaxial tensile strength for large aggregate concrete and wet-screened concrete were 73.499% and 50.21%, respectively, indicating that the frost resistance of large aggregate concrete was poorer than that of wet-screened concrete. On the other hand, the dynamic mechanical properties of concrete under normal conditions are also studied [16-21], but the mechanical performance after freeze-thaw cycles still needs further research. Conclusively, the investigations on dynamic performance of large aggregate concrete after freeze-thaw cycles are of important theoretical and practical meanings for accurately analyzing the reliability of hydraulic structures during service.

In recent researches, the dynamic performance of

large aggregate concrete and wet-screened concrete was studied under seismic load that the range of strain rates was between $10^{-3}/s$ and $10^{-2}/s$. Compared with the statics responses (strain rate of $10^{-5}/s$), the dynamic strain rates were varied from $10^{-5}/s$ to $10^{-2}/s$. A dynamic uniaxial tensile test was carried out on the large aggregate concrete specimens under different freeze-thaw cycles in this paper. And a dynamic uniaxial tensile failure criterion was established by studying the influence of freeze-thaw cycles and the strain rates on the ultimate strength and deformation.

2 METHODS AND EXPERIMENTS

2.1 Materials and concrete mix proportion

All the material qualities meet Chinese national and industrial standards for material parameters. P II 42.5 R ordinary Portland cement from Dalian ONODA cement co., Ltd and grade I fly ash from Dalian were used to prepare all the specimens. Medium sands were used as fine aggregates, and limestones with the continuous graded particle size of 5~80mm were used as coarse aggregates. The water content of sands and gravels were measured before the casting of each batch of specimens. DK-6 high efficiency water reducing agent for concrete developed by Dalian Institute of Building Science was applied. The concrete were mixed with tap water. The water-cement ratio of hydraulic concrete is 0.45. Considering the low strength of massive concrete, C20 was selected as the strength grade of concrete. Referring to the quality requirement of each material in hydraulic concrete in “the design standard of mix proportion of hydraulic concrete” (DL/T533-2005), the mix proportion of the mass concrete in this study is shown in Table 1.

2.2 Specimen preparation and maintenance

The specimens were cast in 250mm×250mm×250mm prismatic wooden molds that were custom-made. Four Φ 20 steel bars were embedded at end of the specimen for the convenience of the connection to the clamps of the testing equipment. The steel bars buried in the concrete were welded together with two rows of Φ 10 stirrups, so as to enhance its overall mechanical performance. The tests were operated based on the

mixing method and the requirements of molding and curing in the “Test code for hydraulic concrete” (SL352-2006). The samples were demoulded after the curing of 48 hours and cured in the static water at 20 ± 3 °C for 90 days. Afterwards, the samples were cured in natural conditions.

2.3 Test equipment and methods

The test is conducted in the TDR-1 freeze-thaw testing apparatus. Freezing-thawing tests were carried out following the “quick frozen method” of the frost resistance tests in “Test code for hydraulic concrete” (SL352-2006). The specimens were soaked in water for 4 days at the temperature of 15~20 °C before being exposed to the freezing-thawing cycles. The center temperature of the specimens should be controlled at (-17 ± 2) °C and (8 ± 2) °C respectively. Since the size of the specimens was large, each freezing-thawing cycle took 7~8 hours to complete. The number of freeze-thaw cycles was 0, 25, 50, 75, and 100 times, respectively. One 260mm×260mm×520mm stainless steel container and two 260mm×720mm×520mm stainless steel containers were used for soaking, which four prism specimens could be placed in at one time.

The dynamic mechanical properties of the specimens were measured by a large static-dynamic triaxial electro-hydraulic servo system, designed by Dalian University of Technology and manufactured by Beijing Foli company. The uniaxial tensile test was conducted at the strain rate of $10^{-5}/s$, $10^{-4}/s$, $10^{-3}/s$ and $10^{-2}/s$ respectively, and the vertical axial tension mode was adopted. Firstly, the specimen was mounted between the loading plates for initial alignment. The specimens were fixed on the loading plates by bolts. Slight eccentricity was corrected with the spherical hinge connected between the loading plate and the loading head of the equipment. Two displacement sensors were installed at both sides of the loading head to measure deformation. And then the specimens were loaded at the predetermined loading rate until it was damaged. At least three specimens were tested for each group for analysis of the results.

Table 1 - Mixture ratio of large aggregate concrete (kg/m³)

Water	Concrete	Fly Ash	Medium Sand	Water Reducer	Broken Stone Diameter (mm)		
					5-20	20-40	40-80
120	214	53	549	8	442.5	442.5	590

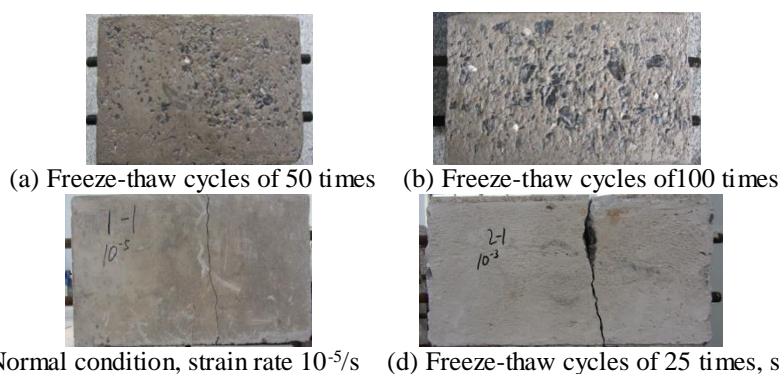


Figure 1 - Morphology of the large aggregate concrete specimens after different freeze-thaw cycles and dynamic uniaxial tensile test

3 FAILURE MORPHOLOGY

Figure 1 (a) and (b) shows the failure modes of the specimens after 50 times and 100 times of freeze-thaw cycles. It was found that part of the coarse aggregates on the surface of the specimens were exposed after 50 cycles of freeze-thaw. After 100 cycles of freeze-thaw, the mortar on the surface of the specimens gradually peeled off, and most of the coarse aggregate were exposed. It was suggested that with the number of the freeze-thaw cycles increasing, the mortar and coarse aggregate on the surface of specimens gradually exposed and peeled off, and the surface peeling was aggravated.

Figure 1 (c) and (d) shows the failure modes of specimens under strain rate of $10^{-5}/s$ in normal condition and strain rate of $10^{-2}/s$ after 25 cycles of freeze-thaw. It can be seen from the experimental results that the fracture surface of uniaxial tensile failure was located in the middle of the specimen, perpendicular to the tensile stress. The failure occurred suddenly without any signal. With increase of strain rate, the cracks widened and the coarse aggregates with tensile failure increased.

4 RESULTS AND DISCUSSION

4.1 Quality characteristics

The mass loss rate of large aggregate concrete after different freeze-thaw cycles is listed in Table 2.

Table 2 - Mass loss rate of large aggregate concrete after freeze-thaw cycles

Number of freezing and thawing	Number of freeze-thaw cycles				
	0	25	50	75	100
Quality (kg)	79.15	78.57	77.46	76.92	76.28
Mass loss rate (%)	0.00	0.73	2.14	2.82	3.63

Mass loss is an evaluation index of the frost resistance of concrete. The testing results showed that the mass loss increased with the increase of freeze-thaw cycles. When the freeze-thawing cycles reached 50 times, mass loss rate increased sharply. Through regression analysis, the relationship between the mass loss rate of large aggregate concrete and the number of freeze-thaw cycles can be expressed with a quadratic curve, as is shown in Equation (1).

$$M_s = a + bN + cN^2 \quad (1)$$

Where M_s is the mass loss rate of concrete specimens after freezing-thawing cycles; N is the number of freeze-thaw cycles; a , b and c are the regression coefficients. According to the regression analysis based on the data in Table 2, the regression coefficient $a=-0.0865$, $b=0.0439$, $c=-7E^{-05}$ and correlation coefficient $R^2=0.9942$, where the formula is in good agreement with the data in the test.

4.2 Strength characteristics

The ultimate tensile strengths of large aggregate concrete specimens under different freeze-thaw cycles and strain rates are shown in Table 3. With the increase of strain rate, the increased percentage of ultimate tensile strength is shown in Figure 2. With the increasing number of freeze-thaw cycles, the loss rate of ultimate compressive strength is presented in Figure 3.

Table 3 - Average uniaxial ultimate tensile strength (MPa)

Number of freeze-thaw cycles	Strain rate			
	$10^{-5}/s$	$10^{-4}/s$	$10^{-3}/s$	$10^{-2}/s$
0	1.478	1.649	1.820	1.928
25	1.392	1.533	1.675	1.779
50	1.307	1.418	1.529	1.630
75	1.154	1.247	1.340	1.411
100	1.002	1.076	1.151	1.190

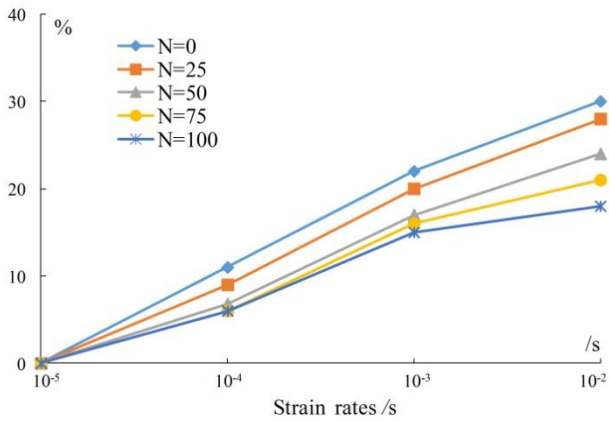


Figure 2 - Increased percentage of uniaxial ultimate tensile strength with the varying strain rate

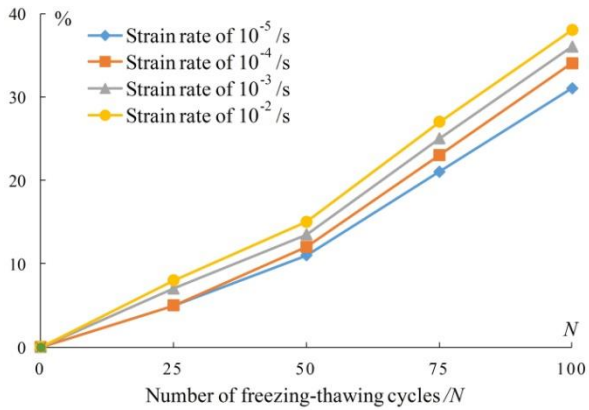


Figure 3 - The loss rate of ultimate tensile strength with freeze-thaw cycles

As can be seen from Table 3, the ultimate tensile strength of large aggregate concrete decreased with the increase of the freeze-thaw cycles under the same strain rate, while it increased with the increase of strain rate under the same freeze-thaw cycles. It may be accounted by the fact that with the increasing strain rate, the increased strength was caused by the broken aggregate due to the insufficient expansion of the internal micro cracks. As can be seen from Figure 2, with the number of freeze-thaw cycles increasing, the increased percentage of the dynamic ultimate strength tended to incline compared with that of static ultimate strength. A possible reason is that the freeze-thaw action prompted the growth of micro cracks in the concrete, and the accumulation of damage increased. According to the Figure 3, the uniaxial tensile strength increased with the increase of freeze-thaw cycle, the loss rate of ultimate tensile strength of large aggregate concrete was the maximum at the strain rate of $10^{-3}/s$ or $10^{-2}/s$. After 100 times of freeze-thaw cycles, the loss rate of strength was the maximum at the strain rate of $10^{-3}/s$ or $10^{-2}/s$, up to 38.30%. Therefore, the influence of dynamic loading rate should be taken into account when designing the mechanical properties of

hydraulic structures.

4.3 Deformation properties

With different freeze-thaw cycles and strain rates, the average strain of the points at peak stress are shown in Table 4.

Table 4 - The uniaxial tensile stress peaks of concrete strain average (10^{-3})

Number of freeze-thaw cycles	Strain rate			
	$10^{-5}/s$	$10^{-4}/s$	$10^{-3}/s$	$10^{-2}/s$
0	1.611	1.255	0.898	0.778
25	1.463	1.113	0.862	0.745
50	1.315	0.971	0.832	0.720
75	1.144	0.870	0.744	0.698
100	0.972	0.769	0.676	0.623

As presented in Table 4, when the freeze-thaw cycles was constant, the peak strain of large aggregate concrete decreased with the increase of strain rate. When the strain rate was constant, the peak strain tended to decrease with the increase of freeze-thaw cycles. A possible reason for the phenomena is that the development internal micro cracks was accelerated and micro cracks increased due to the freeze-thaw process.

With the freeze-thaw cycles of 100 times, the stress-strain curves of uniaxial tensile at different strain rates are shown in Figure 4. With the strain rate of $10^{-2}/s$, the stress-strain curves at different freeze-thaw cycles are shown in Figure 5, where f_t is the stress value.

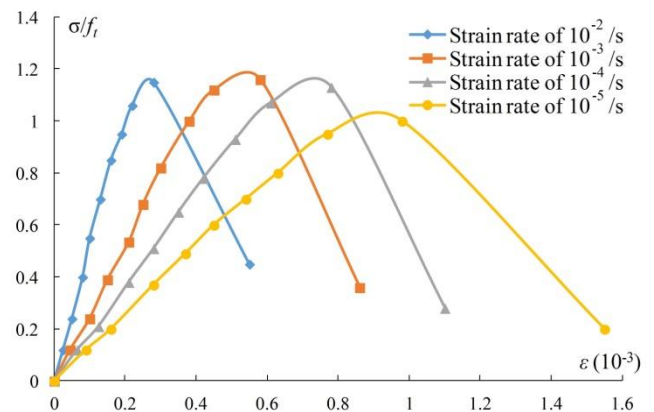


Figure 4 - Stress-strain curves under different strain rates after 100 cycles of freeze-thaw

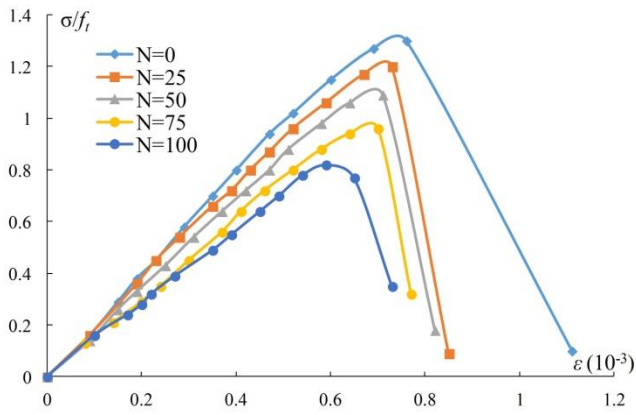


Figure 5 - Stress-strain curves under different freeze-thaw cycles with the strain rate of $10^{-2}/s$

As shown in Figure 4 and Figure 5, with the same freeze-thaw cycles and increased strain rate, the slope of the initial linear section of the stress-strain curves increased gradually, and the curve shrunk and bulged gradually, indicating that the initial elastic modulus increased. The trend of the stress-strain curves under the same strain rate and increased freeze-thaw cycles was similar. With the increase of the strain rate, the points of peak stress gradually moved up and left, and the peak stress increased. With the increase of the freeze-thaw cycles, the points of peak stress gradually moved down and left, and the peak stress decreased, but the corresponding strain decreased.

The expression of the rising section of the uniaxial tensile stress-strain curve of large aggregate concrete is as follows:

$$\frac{\sigma}{\sigma_p} = A_0 + A_1 \frac{\varepsilon}{\varepsilon_p} + A_2 \left(\frac{\varepsilon}{\varepsilon_p}\right)^2 + A_3 \left(\frac{\varepsilon}{\varepsilon_p}\right)^3 \quad (2)$$

Where σ_p is the peak stress of uniaxial tensile, ε_p is the strain of corresponding peak stress, and $A_0, A_1, A_2,$ and A_3 can be determined by the boundary conditions of the rising section in the stress-strain curve:

A_0 : when the curve passes through the origin, $\sigma=0,$
 $\varepsilon=0$;

A_1 : when the curve passes through the peak point $P,$
 $\sigma=\sigma_p, \varepsilon=\varepsilon_p$;

A_2 : taking the derivation of ε at the origin in Equation (2), $\left. \frac{d\sigma}{d\varepsilon} \right|_{\varepsilon=0} = E_0$;

A_3 : taking the derivation of ε at the peak point P in Equation (2), $\left. \frac{d\sigma}{d\varepsilon} \right|_{\varepsilon=\varepsilon_p} = 0$.

By the above four boundary conditions, it can be calculated that: $A_0=0, A_1=E_0/(\sigma_p/\varepsilon_p)=E_0/E_s, A_2=3-2A_1,$ and $A_3=A_1-2$.

Where E_s is the secant modulus at the point of the stress peak, E_0 is the initial elastic modulus of

concrete, and it is substituted by the secant modulus at the 50% σ_p point in the rising section of the stress-strain curves.

The data of uniaxial tensile test of large aggregate concrete was fitted according to the constitutive relation in Equation (2). Some results are shown in Equation (3) and (4), which is in a good agreement with the experimental data.

For 75 cycles of freeze-thaw and the strain ratio of $10^{-2}/s$:

$$\frac{\sigma}{\sigma_p} = 0.9299 \frac{\varepsilon}{\varepsilon_p} + 0.1817 \left(\frac{\varepsilon}{\varepsilon_p}\right)^2 - 0.112 \left(\frac{\varepsilon}{\varepsilon_p}\right)^3, R^2 = 0.9987 \quad (3)$$

For 100 cycles of freeze-thaw and the strain ratio of $10^{-3}/s$:

$$\frac{\sigma}{\sigma_p} = 1.1963 \frac{\varepsilon}{\varepsilon_p} + 0.7397 \left(\frac{\varepsilon}{\varepsilon_p}\right)^2 - 0.9323 \left(\frac{\varepsilon}{\varepsilon_p}\right)^3, R^2 = 0.9981 \quad (4)$$

4.4 Failure criterion

4.4.1 The relationship between uniaxial tensile strength and strain rate

According to the regression analysis, the expression of the relationship between the uniaxial tensile strength and the strain rate of large aggregate concrete can be obtained:

$$f_t / f_{ts} = a + b \log(\dot{\varepsilon}_t / \dot{\varepsilon}_{ts}) \quad (5)$$

Where f_t is the dynamic tensile strength, f_{ts} is the static tensile strength, $\dot{\varepsilon}_t$ is the dynamic strain rate, $\dot{\varepsilon}_{ts}=10^{-5}/s$ is the static strain rate, a, b are the fitting parameters. When the freeze-thaw cycles is 100 times, for example, the regression coefficients and correlation coefficients of the formula are: $a=1.0069,$ $b=0.0638; R^2=0.982,$ respectively. The comparison between the calculated and experimental results at different cycles is showed in Figure 6(a), indicating that the calculation results agree well with the experimental results.

4.4.2 The relationship between the uniaxial tensile strength and freeze-thaw cycles

Through regression analysis, the relationship between the ratio of uniaxial tensile strength f_t^D/f_t and the number of freeze-thaw cycles N is as follows:

$$f_t^D / f_t = a + bN + cN^2 \quad (6)$$

Where: f_t^D is the uniaxial tensile strength after freeze-thaw cycles, f_t is the uniaxial tensile strength under normal conditions, N is the number of freeze-thaw cycles, and a, b, c are the fitting parameters.

When the strain rate is $10^{-2}/s$, for example, the regression coefficients and correlation coefficients are $a=0.9989, b=-0.0026, c=-1E^{-05};$ and $R^2=0.9992,$ respectively. The comparison between the calculated

and experimental results at different strain rates is showed in Figure 6 (b), manifesting that the calculation results are in a good agreement with the experimental results.

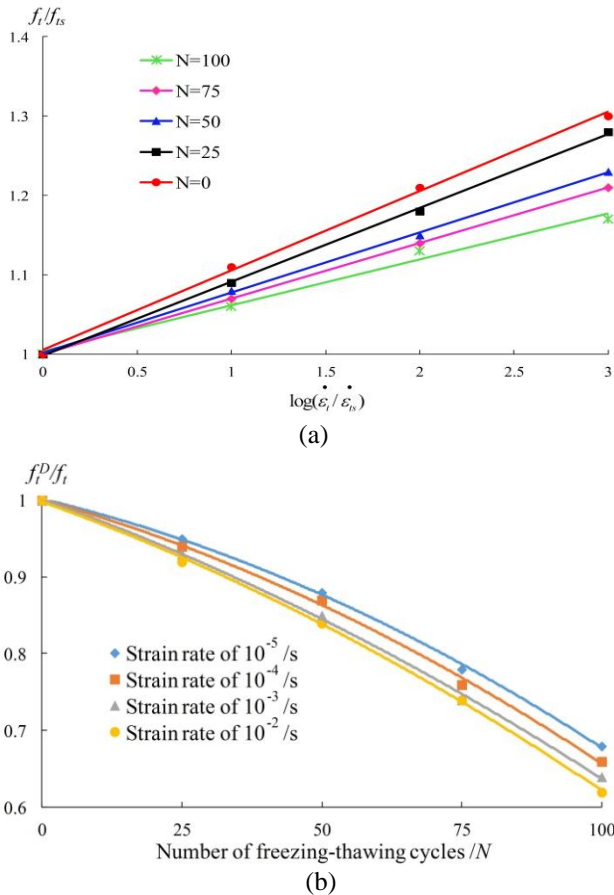


Figure 6 - Comparison chart of test data and failure criterion

4.4.3 Failure criterion for the freeze-thaw cycles and strain rates

It is necessary to establish the unified failure criterion of large aggregate concrete for hydraulic structures in practice with the consideration of freeze-thaw cycles and strain rate, and the expression is as follows.

$$f_t^D/f_{ts} = a \log(\dot{\epsilon}_d/\dot{\epsilon}_s) + b + cN + dN^2 \quad (7)$$

Where: f_t^D is the dynamic uniaxial tensile strength after freeze-thaw cycles, f_{ts} is the static tensile strength under normal conditions. It can be obtained that $a=0.0729$, $b=1.053$, $c=-0.002754$, $d=-1.413e^{-05}$ with the correlation coefficient $R^2=0.9788$ by statistical regression using MATLAB software. It can be seen that the calculated results are in good agreement with the experimental data.

5 CONCLUDING REMARKS

Based on the experimental results of dynamic uniaxial tensile properties of large aggregate concrete after freezing-thawing cycles presented in this paper, the following conclusions can be drawn:

1. With the constant strain ratio, uniaxial ultimate tensile strength of large aggregate concrete decreased with the increase of freeze-thaw cycles. With the constant number of freezing-thawing cycles, the uniaxial ultimate tensile strength increased with the increase of strain rate. With the number of freeze-thaw cycles increasing, the increasing percentage of the dynamic ultimate strength tended to decline gradually compared with that of the static ultimate strength. The loss rate of ultimate tensile strength of large aggregate concrete was the maximum at the strain rate of $10^{-3}/s$ or $10^{-2}/s$ after different freeze-thaw cycles. Therefore, the influence of dynamic loading rate should be taken into account when designing the mechanical properties of hydraulic structures.
2. Under the same freeze-thaw cycles, the peak strain of uniaxial tensile decreased with the increasing strain ratio. Under the same strain ratio, the peak strain of uniaxial tensile decreased with the increasing freeze-thaw cycles. The rising section of the stress-strain curves obtained in the test can be fitted with a cubic curve based on the initial elastic modulus of concrete and the secant modulus at the stress peak point, where the fitting results are good.
3. With the consideration of freezing-thawing cycles and strain rate, the failure criterion is in good agreement with the experimental data, which can provide theoretical reference for the design, maintenance and life prediction of hydraulic structures.

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