Experimental Analysis on the Influence of Freeze-thaw Cycle on the Dynamic Deformation Characteristics of Silty Clay on the Qinghai-Tibet Railway

Lihui Tian

School of Civil Engineering, Harbin Institute of Technology,
Harbin, 150090, Heilongjiang, China;
School of Mining Engineering, Heilongjiang University of Science and Technology,
Harbin, 150022, Heilongjiang, China

Lina Wang

College of Architecture and Civil Engineering, Yunnan Agricultural University,
Kunming, 650201, Yunnan, China

Xianzhang Ling

School of Civil Engineering, Harbin Institute of Technology,
Harbin, 150090, Heilongjiang, China;
State Key Laboratory of Frozen Soil Engineering, Chinese Academy of Sciences,
Lanzhou 730000, Gansu, China

Feng Zhang

School of Civil Engineering, Harbin Institute of Technology,
Harbin, 150090, Heilongjiang, China

Abstract

Dynamic triaxial test at room temperature is performed and the influence of the joint action of freeze-thaw cycle and train load is analyzed. This article studied the influence of the number of freeze-thaw cycles, the melting temperature and amplitude of dynamic stress on the resilient deformation and accumulated permanent deformation of the silty clay along the

Qinghai-Tibet Railway. According to the analysis results, (1) As the number of freeze-thaw cycles increases, the accumulative plastic strain of the silty clay on the Qinghai-Tibet Railway grows with the increase of the number of vibration. Meanwhile, its failure mode slowly evolves from brittle failure to plastic failure; (2) Resilient strain shows a growing trend with the increase of the number of freeze-thaw cycles and the corresponding resilient modulus is declining, but the effect of freeze-thaw cycles is larger than that of the last two factors, both showing only mild changes; (3) As the temperature during thawing rises, the accumulative plastic strain increases, which causes the rise of resilient strain and the drop of the corresponding resilient modulus; the larger the dynamic strain amplitude, the greater the influence of temperature during thawing on accumulative plastic strain is

Key words: QINGHAI-TIBET RAILWAY, SILTY CLAY, FREEZE-THAW CYCLES, DYNAMIC DEFORMATION, DYNAMIC TRIAXIAL TEST

1. Introduction

Due to seasonal alteration, frozen soil can thaw and freeze as the temperature rises and falls around 0℃ level. This constant alternation of freeze and thaw is generally called freeze-thaw cycle, also known as multigelation. The differences of the properties of frozen soil and thawed soil are mainly caused by the temperature effect of water and soil skeleton, but major changes can occur to the physical and mechanical properties of frozen water [1]. Therefore, freeze-thaw action not only affects the soil's physical properties such as permeability, dry density and void ratio, but also affects its intensity and deformation characteristics. At present, domestic research mainly concentrates on the influence of freeze-thaw cycles on silty clay's physical properties and static characteristics [2, 3, 4].

However, the research considering the influence of freeze-thaw cycles on the mechanical properties of silty clay is lacking. What is even more rare is the overall analysis of the influence of freeze-thaw cycles and train load on the elastic deformation characteristics and long-term accumulative deformation characteristics of silty clay [5, 6, 7].

Targeting the widely distributed silty clay along the Qinghai-Tibet railway, we performed dynamic triaxial test at room temperature, with an emphasis on the joint action of freeze-thaw cycle and train load. This article studies the influence of the number of freeze-thaw cycles and temperature during thawing and gives overall consideration to the influence of factors such as amplitude of dynamic stress on the resilient deformation and accumulated permanent deformation of the silty soil along the Qinghai-Tibet Railway.

2. Test materials and specimen preparation

2.1. Test materials

The test soil samples were silty clay widely distributed along the Qinghai-Tibet Railway. The liquid limit, plastic limit, plastic index and relative density were 26.1%, 17.3%, 8.8 and 2.57, respectively. Refer to Figure 1 for grain composition curve.

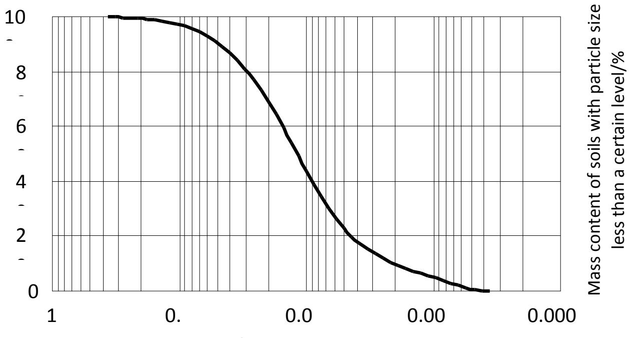


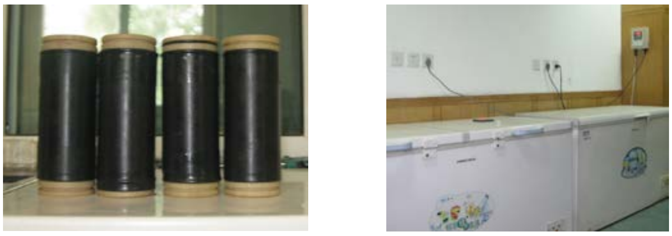
Figure 1. Grain composition curve of the silty clay along the Qinghai-Tibet Railway

2.2. Specimen preparation

According to Chinese Standard for Soil Test Method (GB/T50123-1999), this research remolded silty clay and prepared test samples with artificial freezing method. The soil samples were first prepared into wet soil with an initial moisture content of 12.4% (optimum moisture content) and then crushed into test samples with a diameter of

61.8 mm, a height of 125 mm and a dry density of 1.89g/cm^3. After quickly frozen under the temperature of -30℃ for 24h, the samples were treated by the constant test temperature for 24h. Refer to Figure 2 for the preparation process of test samples. In order to make the test results more comparable, the temperature of the test samples was kept consistent. The test samples for each set of tests were put in the same thermostat. The thermostat was retrofitted from freezer and the thermostat was calibrated before test [4].

(a)Three-flap instrument (b) Air exhaust and water saturation



(c) Preparation of test samples (d) Thermostat

Figure 2. The preparation of test samples

3. Test method

3.1. Test instrument

Relevant laboratory tests were performed with MTS-810 triaxial test machine manufactured by State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environment and Engineering Research Institute of Chinese Academy of Sciences. See Figure 3[4]. This instrument was equipped with low temperature confining pressure system, circulation cooling system, and automatic computer numerical control and data collection system. The major technical indicators were: maximum axial load 100 kN, stable confining pressure 0.3～20MPa, maximum axial displacement ±85mm, loading frequency range, 0～50Hz, and temperature range room temperature～-30℃[4].

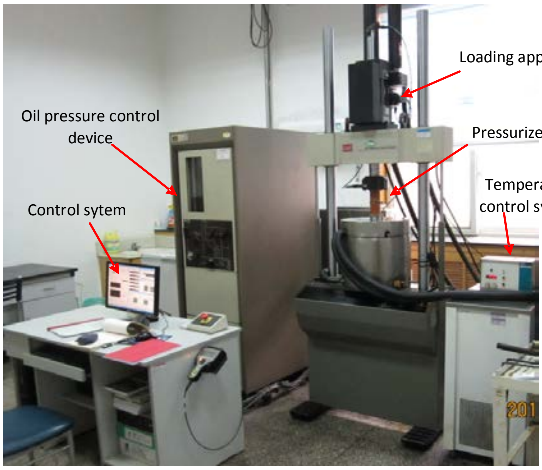


Figure 3. Low temperature dynamic triaxial test machine

3.2. Test loading scheme

According to the existing field monitoring results, the dynamic pressure of subgrade soil has a shape similar to half sine wave [8]. So this research simulated the one-way pulse stress of subgrade soil under the effect of train load by loading sine wave with one-way circulation, as shown in Figure 4. Due to the fact that at the moment of train cyclic loading, the pore water in the subgrade soil cannot be discharged timely.

Therefore, undrained isotropic consolidation conditions were adopted [9].

According to the monitoring data and relevant laboratory tests of the roadbed temperature of the Qinghai-Tibet Railway [10, 11, 12], freeze-thaw cycle under closed system was used. Samples were quickly frozen under minimum negative temperature of -11℃ for 24 hours and then taken out and treated under room temperature 20±2℃ until complete thawing. Thus, one freeze-thaw cycle was completed. The above operation was repeated until the required number of freeze-thaw cycles was completed, as shown in Figure 5.

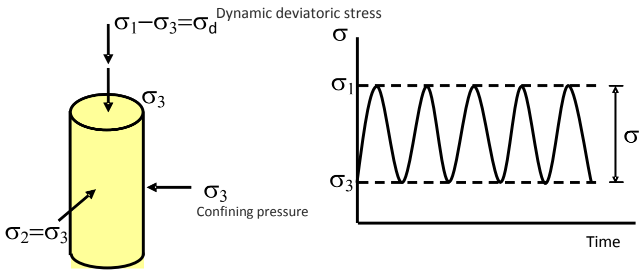


Figure 4. Scheme of train loading

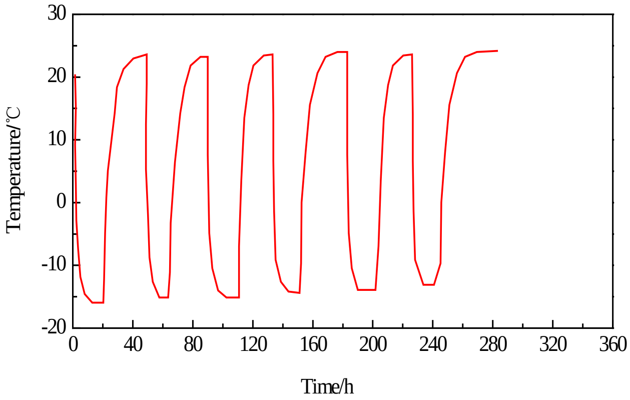


Figure 5. Ambient temperature during freeze-thaw cycles

Based on the freeze-thaw cycle test conditions for the silty clay along the Qinghai-Tibet Railway, dynamic stress was applied on each sample and the samples were loaded for 10, 000 times until the accumulative plastic strain of each sample reached 8%, the failure limit of the samples. Refer to Table 1 for concrete test plan.

Table 1. Dynamic triaxial test design for thawing silty clay

Confining pressure (MPa)	Number of freeze-thaw cycles	Amplitude of dynamic stress (kPa)	Temperature during thawing (℃)
0	0	300, 360, 400, 440, 500	20
0	1	200, 240, 300, 400	20
0	2	150, 200, 240, 300, 400	20
0	4	150, 200, 240, 300	20
0	6	150, 180, 200, 240	20
0	1	200, 300, 400	7
0.3	2	300, 400, 560, 720	20
0.4	2	400, 560, 720, 800	20

4. Analysis of test results

4.1. Influence of the number of freeze-thaw cycles on the deformation characteristics of silty clay

Relation curve of accumulative plastic strain and vibration numbers for the silty clay on the Qinghai-Tibet Railway under different numbers of freeze-thaw cycles is shown in Figure 6. According to the Figure, when the amplitude of dynamic stress is 300kPa, the silty clay samples without undergoing freeze and thaw shows small accumulative plastic strain and the strain is basically elastic strain. After two freeze-thaw cycles, thawed soil shows slow growth of accumulative plastic stress at the beginning of vibration. After some time of cyclic loading, there appears an inflection point on the relation curve between the accumulative plastic strain and vibration numbers of the thawed soil and later a sharp increase which is leads to failure.

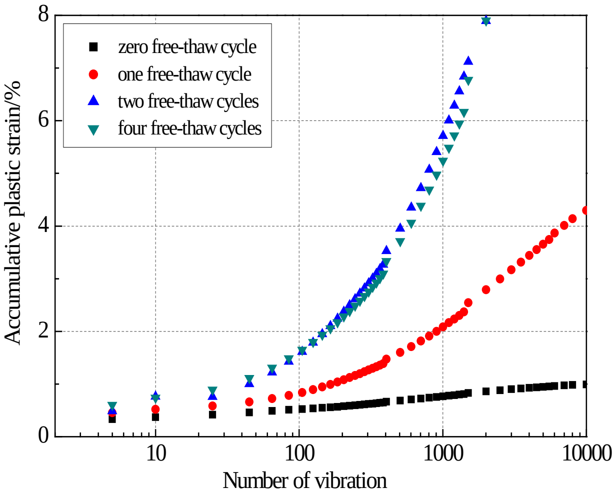


Figure 6. Relationship between accumulative plastic strain and number of vibrations under different number of freeze-thaw cycles

Figure 7 is the relation curve between the amplitude of dynamic stress and accumulative plastic strain when the number of freeze-thaw cycles is 0, 1, 2, 4 and 6, respectively. As shown in Figure 7(a), for the soil samples undergoing one and four freeze-thaw cycles, when the amplitude of dynamic stress is 200kPa and the number of vibrations is 100, the corresponding accumulative plastic strain is 0.352% and 0.693%, respectively, with a difference of 0.341%. When other conditions are the same and the amplitude of dynamic stress is 240kPa and 300kPa, the difference of accumulative plastic strain is 0.544% and 1.113%, respectively. It can be seen that with the rise of amplitude of dynamic stress, the number of freeze-thaw cycles exerts an increasing influence on the accumulative plastic strain of the silty clay along the Qinghai-Tibet Railway.

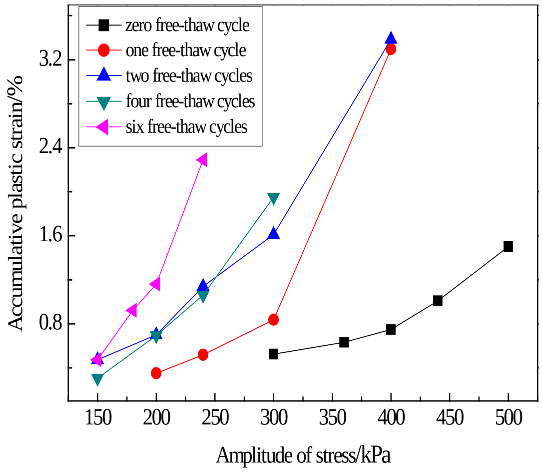
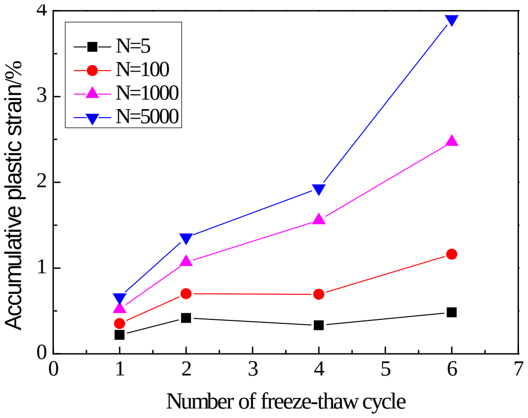
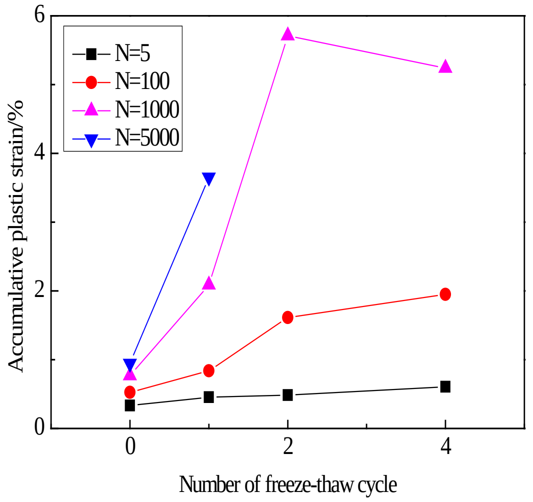


Figure 7. Relationship between amplitude of dynamic stress and accumulative plastic strain under different number of freeze-thaw cycles



(a) σ_d =200kPa



(b) σ_d =300kPa

Figure 8. Relationship between the number of freeze-thaw cycles and accumulative plastic strain

In order to further study the influence of freeze-thaw cycles on the accumulative plastic strain of the silty clay along the Qinghai-Tibet Railway, the curve of the accumulative plastic strain of silty clay undergoing 0, 1, 2, 4 and 6 freeze-thaw cycles is shown in Figure 8. It can be seen from the Figure that the number of freeze-thaw cycles has a major impact on the accumulated permanent deformation of the soil body under long-term load effect. When the amplitude of dynamic stress is 200kPa, with the gradual increase of the number of freeze-thaw cycles, the permanent strain of subgrade soil shows an apparent growing trend. When the amplitude of dynamic stress increases to 300kPa, the accumulative plastic strain shows a growing trend in the first two freeze-thaw cycles. Later the accumulative plastic strain changes very little with the increase of the number of freeze-thaw cycles.

Figure 9 and Figure 10 show the relationship of amplitude of dynamic stress with resilient strain and modulus of elasticity when the number of vibrations is 100 and under different freeze-thaw cycles. Figure 11 and Figure 12 show the influence of the number of freeze-thaw cycles on the resilient strain and modulus of resilience of silty clay along the Qinghai-Tibet Railway. It can be seen from the Figure that when the number of freeze-thaw cycle is less than 3, resilient strain grows with the increase of the number of freeze-thaw cycles and the corresponding modulus of resilience shows a downward trend. However, when the number of freeze-thaw cycles is more than three, resilient strain and the corresponding modulus of resilience do not change considerably with the increase of the number of freeze-thaw cycles. This is because cyclic freeze-thaw action can lead to the changes in the original structure of the soil body of the silty clay along the Qinghai-Tibet Railway. The samples selected for the test were small-sized. During freezing, rapid cooling would cause the failure of the water in the soil body to transport. As a consequence, the water froze in the original position. Freezing can make the volume of soil body larger, but frozen soil cannot restore the pre-freeze state due to enlarged void. This results in loose soil body and a reduction of modulus of resilience. In the first few freeze-thaw cycles, there is a dramatic decline in the modulus of resilience. After several cycles, the voids approach a steady state, which slows down the attenuation of the modulus of resilience of the soil body.

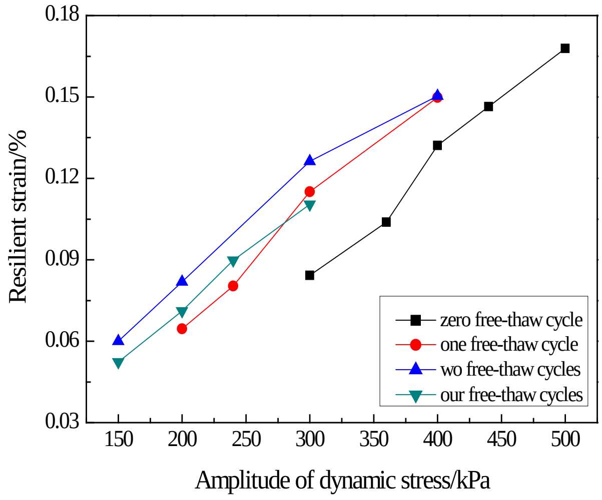


Figure 9. Relationship between amplitude of dynamic stress and resilient strain under different numbers of freeze-thaw cycles

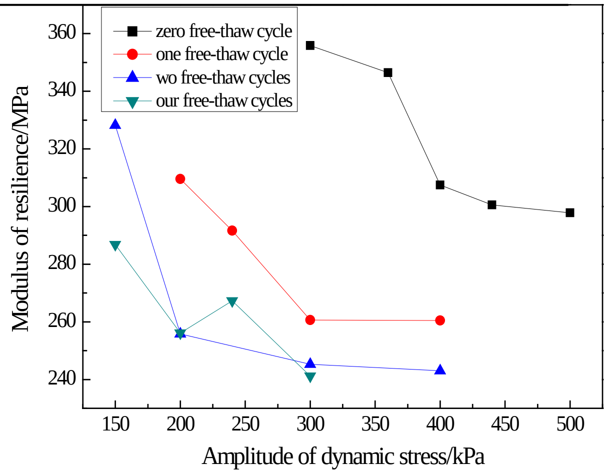


Figure 10. Relationship between amplitude of dynamic stress and modulus of resilience under different numbers of freeze-thaw cycles

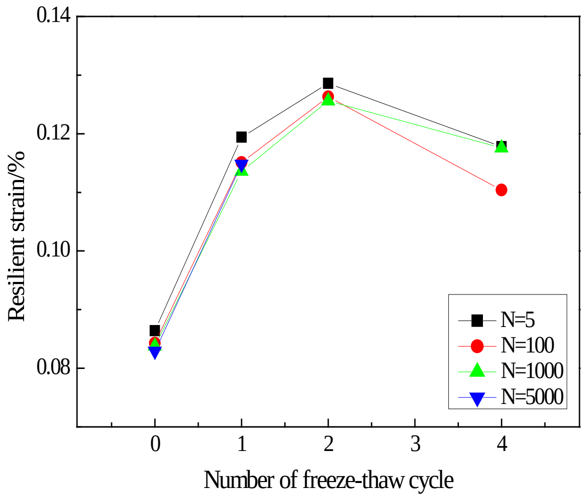


Figure 11. Relationship between the number of freeze-thaw cycles and resilient strain

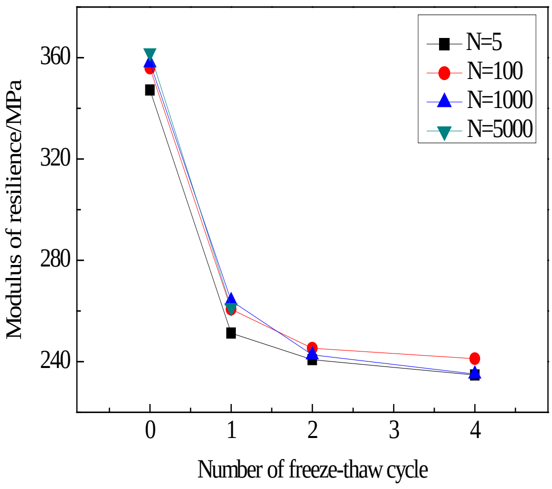


Figure 12. Relationship between the number of freeze-thaw cycles and modulus of resilience

4.2. Influence of temperature during thawing on the deformation characteristics of silty clay

Figure 13 shows the relationship between accumulative plastic strain and the number of vibrations for different stress amplitude at the temperature of 7℃ and 20℃ with only one freeze-thaw cycle. As shown in the Figure, with the rise of temperature during thawing, accumulative plastic strain also increases, but the general relationship between accumulative plastic strain and the number of vibrations stays unchanged. When the amplitude of dynamic stress is 200kPa, the number of vibration is 1, 000 and the temperature during thawing is 7℃ and 20℃, the accumulative plastic strain is 0.445% and 0.521%, respectively, with an increase of 0.076%. With other conditions unchanged, if the amplitude of dynamic stress is 300kPa, the corresponding accumulative plastic strain is 1.293% and 2.086%, respectively, with a growth of 0.793%. Thus it can be seen that the larger the amplitude of dynamic stress, the greater the impact of temperature during thawing on the accumulative plastic stress will be.

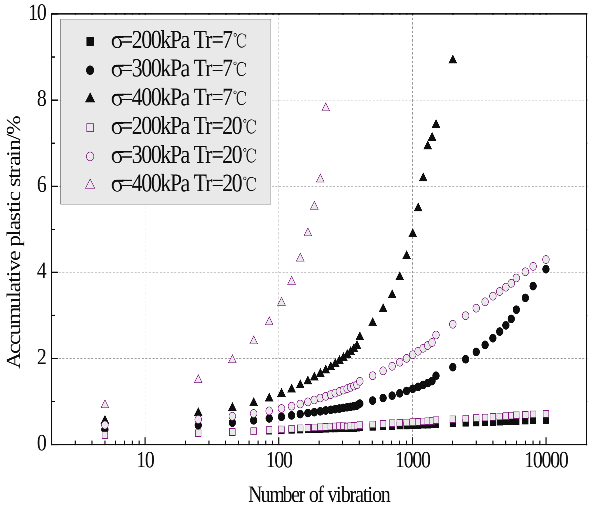


Figure 13. Relationship between accumulative plastic strain and the number of vibrations at after one freeze-thaw cycle

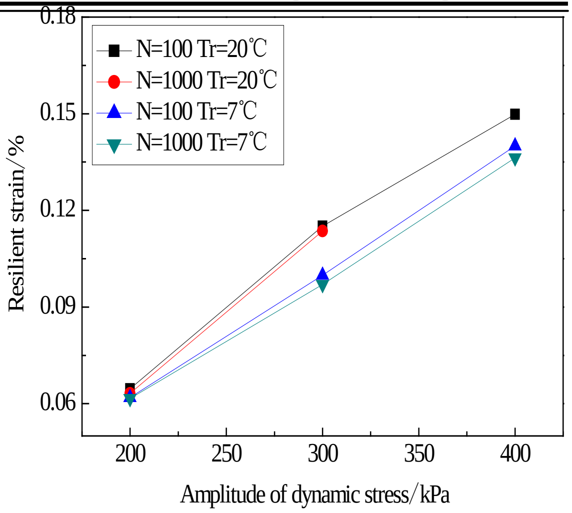


Figure 14. Effect of temperature during thawing on resilient strain

Figure 14 and Figure 15 show the influence of temperature during thawing on resilient strain and modulus of resilience. As shown in the Figure, when the number of vibrations is 100, amplitude of dynamic stress is 200kPa and temperature during thawing is 7℃, the resilient strain of the silty clay along the Qinghai-Tibet Railway is 0.0619% and the corresponding modulus of resilience is 323.2MPa. When the temperature during thawing is 20℃, the resilient strain and modulus of resilience are 0.0646% and 309.6MPa, respectively. The above analysis shows temperature during thawing has some influence on the resilient strain and modulus of resilience of the silty clay along the Qinghai-Tibet Railway. With the rise of temperature during thawing, the resilient strain of samples increases, and the modulus of resilience reduces.

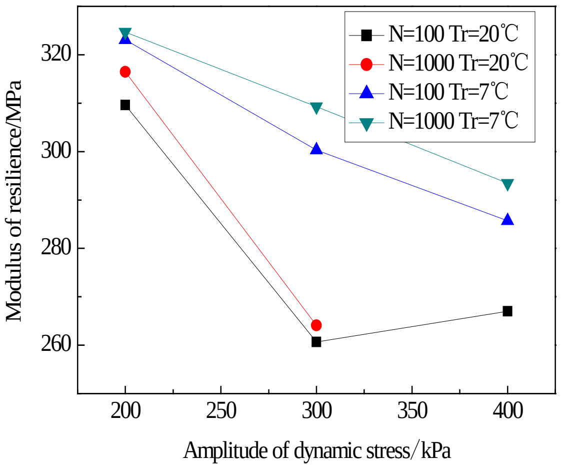


Figure 15. Effect of temperature during thawing on modulus of resilience

5. Conclusions

Based on the silty clay along the Qinghai-Tibet Railwa, dynamic triaxial test under room temperature has been performed. The joint influences of the number of freeze-thaw cycles, temperature during thawing, amplitude of dynamic stress, confining stress and the number of vibration on the accumulative plastic deformation, resilient strain and modulus of resilience of the silty clay along the Qinghai-Tibet Railway have been studied. The following were the main conclusions:

(1) When the number of freeze-thaw cycles was less than four, the accumulative plastic strain strain of silty clay along the Qinghai-Tibet Railway sharply increased with the increase of the number of vibrations to reach the failure limit, and brittle failure occurs; but when the number of freeze-thaw cycle was six, the accumulative plastic strain of silty clay would gradually grow with the increase of the number of vibrations until failure, and plastic failure occurs. Thus it can be seen that as the number of freeze-thaw cycles increased, the failure mode of silty clay gradually would evolved from brittle failure to plastic failure.

(2) The number of freeze-thaw cycles has a major impact on accumulated permanent deformation under long-term load effect. When the amplitude of dynamic stress was 200kPa, as the number of freeze-thaw cycles gradually increases, the permanent strain of the roadbed soil has shown a significant increase. When the amplitude of dynamic stress increased to 300kPa, accumulative plastic strain has shown a growing trend in the first two freeze-thaw cycles but did not change much afterwards with the increase of freeze-thaw cycles.

(3) Resilient strain has shown a growing trend after two freeze-thaw cycles, but the modulus of resilience declined. The resilient strain and modulus of resilience have not change considerably when the numbers of the freeze-thaw cycles were more than two.

(4) With the rise of temperature during thawing, accumulative plastic strain has increased, but the relationship between accumulative plastic strain and the number of vibrations stayed basically constant. The larger the amplitude of dynamic stress, the greater the influence of temperature during thawing on accumulative plastic strain would be. With the rise of temperature during thawing, the resilient strain of samples has increased and the modulus of resilience decreased.

Acknowledgements

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