

Shear strength characteristics at different temperatures of Shenshuo Railway subgrade filling

ZHANG Zhi-chun¹, LI Xu², TIAN Ya-hu², WEI Chao-xiong¹, ZHANG Guo-guang³

(1. Shenshuo Railway Branch, China Shenhua Energy Co., Ltd., Yulin 719316, Shaanxi, China;

2. School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China;

3. Jinan Railway Bureau, Jinan 250000, Shandong, China)

Abstract: With the increase of axle load, the instability failure of heavy haul railway subgrade is becoming more and more prominent. In order to obtain the shear strength of the subgrade filling of Shenshuo Railway at different temperatures, a series of direct shear tests were conducted by the large direct shear apparatus, which was developed in the Frozen Soil Laboratory of Beijing Jiaotong University. The subgrade filling is low liquid limit silt, the optimum moisture is 14.5%, which was selected as the moisture content of samples, and the compaction coefficient is 0.95. Three temperature levels of positive temperature, $-3\text{ }^{\circ}\text{C}$ and $-5\text{ }^{\circ}\text{C}$ were set up, and four different vertical pressures were selected to be tested. Based on the test results, the changes and regulations of various characteristics, such as shear stress-displacement, internal friction angle, cohesion and shear dilatancy, were analyzed. The results show that the cohesion of subgrade filler is strongly influenced by the cooling temperature. Cohesion of subgrade filling at $-3\text{ }^{\circ}\text{C}$ is over 500 kPa than that at positive temperature, and is 95.5 kPa less than that at $-5\text{ }^{\circ}\text{C}$. With the temperature decreasing from positive temperature to $-5\text{ }^{\circ}\text{C}$, the internal friction angle increases from 19.6° to 33.8° . Under the conditions of different temperatures and different vertical pressures, curves of shear stress-displacement are basically the same, which can be divided into consolidation stage, partial shear stage and failure stage. The shear strength of subgrade filling of Shenshuo Railway is significantly affected by cooling temperature. In frozen state, the maximum increase of shear strength is more than 400% compared with the unfrozen state. Even if they are all frozen at negative temperature, the shear strength also increases with the decrease of cooling temperature. The subgrade filling in frozen state shows obvious shear dilatancy. With the increase of vertical pressure, the shear dilatancy becomes decreasing. However, it has no obvious change with the cooling temperature. 4 tabs, 5 figs, 20 refs.

Key words: subgrade engineering; subgrade filling; direct shear experiment; shear strength characteristic; shear dilatancy; displacement

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神朔铁路路基填料在不同温度条件下的抗剪特性

张志春¹, 李 旭², 田亚护², 魏朝雄¹, 张国光³

(1. 中国神华能源股份有限公司 神朔铁路分公司, 陕西 榆林 719316; 2. 北京交通大学
土木建筑工程学院, 北京 100044; 3. 济南铁路局, 山东 济南 250000)

摘 要:随着列车轴重的不断增加,重载铁路路基的失稳破坏问题越来越突出,针对此现象,研究了神朔铁路路基填料在不同温度条件下的抗剪特性,采用北京交通大学冻土实验室自行研发的大型温控冻融界面直剪仪设计了一系列的直剪试验。该路基填料为低液限粉土,最优含水率取14.5%,压实系数取0.95,设置正温、-3℃、-5℃这3个温度等级,各选取4个不同的垂直压力进行试验。基于试验结果,详细分析了剪应力-剪切位移关系特征曲线、内摩擦角、黏聚力以及剪胀性等各项土体抗剪特性指标的变化及规律。研究结果表明:该路基填料的黏聚力受冷却温度的影响显著,在-3℃时的黏聚力比正温条件下大500 kPa,比-5℃条件下小95.5 kPa;随着冷却温度从正温降到-5℃,土体内摩擦角从19.6°增大到33.8°;不同温度及不同垂直压力条件下路基填料的剪应力-剪切位移关系曲线形态基本一致,均可分为压密、局部剪切和剪切破坏3个阶段;神朔铁路路基填料的抗剪强度受冷却温度的影响明显,冻结状态下抗剪强度较未冻结状态时的最大增幅达到400%以上,即便同为负温冻结状态,抗剪强度也会随冷却温度的降低而增大;路基填料在冻结状态下表现出明显的剪胀性,并且随着垂直压力的增大,剪胀性表现出明显的下降趋势,但是并没有随冷却温度的不同而产生明显的差异。

关键词:路基工程;路基填料;直剪试验;抗剪特性;剪胀性;位移

0 Introduction

Shenshuo Railway is located in Northwest China and is one of the major west-to-east pathways for transporting coal. Because of longer duration of winter and lower temperature, a large range of seasonal frozen soil region occurs annually. Lai, et al. explained that frozen soil had complex properties and its mechanical properties were very different from the unfrozen soil^[1]. For frozen soil region, the shear strength of frozen soil was one of the most important physical and mechanical indexes, which had a direct effect on the stability of frozen soil foundation, slope and retaining wall^[2]. Research methods on shear strength of frozen soil mainly included triaxial compressive test, torsion test, spherical die test, direct shear test and so on^[3-7]. Zhang, et al. carried out a series of torsion tests of frozen loess in Lanzhou and discussed the primary properties such as shear modulus, shear strength, and flowability, which varied with temperature and rotating speed^[8]. Czurda, et al. studied the effects of freezing time and freezing tempera-

ture on shear strength of clay under open and closed systems^[9]. Liang, et al. analyzed the instantaneous compressive strength and shear strength of frozen sandy soil by using the WE-60 universal material testing machine^[10]. Chen accomplished a series of triaxial shear test and made a thorough analysis on the instantaneous shear strength of frozen clay when the soil temperatures varied from -5℃ to -25℃^[11]. Zhang, et al. developed a multifunctional frozen triaxial test apparatus, and used it to study the shear strength and creep properties of sandy clay^[12].

Among the studies demonstrated above, the size of soil specimen was small and its stress boundary condition was not being considered, because the size and the boundary both had an obvious effect on soil strength, meanwhile, there was few research on shear dilatancy of frozen soil. Accordingly, in this paper the subgrade filling of Shenshuo Railway was selected for indoor direct shear test, in which the freezing-thawing interface could be controlled by the large direct shear apparatus. Based on the test results, the mechanical characteristics of frozen soil were studied and the

influences on freezing-thawing circle were discussed. The research results are of great importance for the maintenance and disease prevention of Shenshuo Railway subgrade.

1 Test instrument and scheme

1.1 Test instrument

At normal temperature, the direct shear test of soil is easy to be realized. However, under the condition of negative temperature, the direct shear test will become difficult, due to intricate temperature control system.

Compared to the regular direct shear test, the large-scale model test may not only improve the stress condition of soil boundary, but also overcome the influence of the size effect and the boundary effect^[13]. Therefore, the large-scale direct shear test is closer to actual working conditions and its results are more reliable and reasonable.

In this experiment, a large-scale direct shear apparatus with temperature control system, in which the clearance size of shear box was 300 mm in length, 300 mm in width and 200 mm in height, was used in the Frozen Soil Laboratory of Beijing Jiaotong University (Fig. 1).

The upper and lower shear boxes are wrapped by refrigeration sets respectively and connected with the temperature control system through pipes, hence, the temperature of soil in box can be controlled accurately.

Under the vertical and horizontal loading, the shear strain of soil can be monitored automatically by monitoring systems.

1.2 Field sampling and testing of basic physical parameters

Based on the subgrade disease of Shenshuo Railway, soils were sampled from three different parts of subgrade on site, the surface layer, the bottom layer and the basement of subgrade.

By the test in laboratory, the maximum dry density, specific gravity, liquid limit and plastic index of soil sample are 1.886 g/cm³, 2.754, 25.2% and 8, respectively. The maximum particle size is no more than 2 mm, and the particle size distribu-

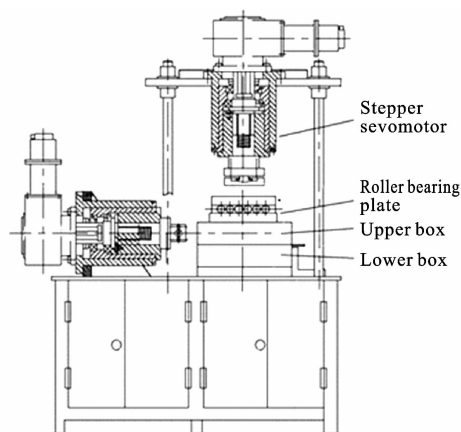


Fig. 1 Schematic of large direct shear apparatus with freezing-thawing interface under temperature control

图 1 大型温控冻融界面直剪仪示意

tion curve of subgrade filling is shown in Fig. 2. It can be seen that $P(d < 0.075 \text{ mm}) = 71.92\%$ ($d < 0.075 \text{ mm}$ means that the percentage of accumulated mass of the particle P whose diameter d is no more than 0.075 mm in total mass), $P(d \geq 0.075 \text{ mm}) = 28.08\%$. According to *standard for engineering classification of soil* (GB/T 50145—2007)^[14] and *code for design on subgrade of railway* (TB 10001—2005)^[15], the subgrade filling is low liquid limit silt. In addition, the uneven coefficient $C_u = d_{60}/d_{10} = 4.631$, the curvature coefficient $C_c = d_{30}^2/(d_{60}d_{10}) = 0.175$, d_{10} , d_{30} , d_{60} means that soil particles contents are less than 10%, 30%, 60% of the total amount of soil samples, the two calculated values are less than 5 and 1, respectively, which means the particle size distribution is uniform and there is no much difference between particle sizes. Namely, both the lack of intermediate grain diameter and too much smaller particles result in a bad gradation of the subgrade filling.

1.3 Test scheme

The optimum moisture content 14.5% is selected as the moisture content of samples. Due to the low strength of thawed soil, when the vertical pressure is 200 kPa, the shear failure of soil sample is obtained easily and the shear rate is much higher, the compaction coefficient 0.95. Therefore, 400, 600, 800 and 1 000 kPa were selected as vertical pressure p for thawed soil, as shown in Tab. 1.

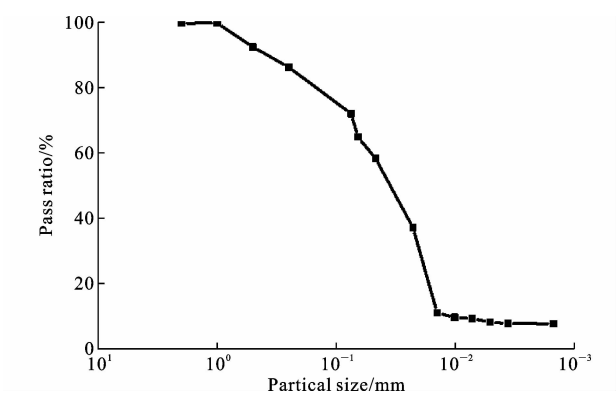


Fig. 2 Particle size distribution curve of subgrade filling

图 2 路基填料颗粒级配曲线

Tab. 1 Test schedule

表 1 试验方案

Temperature/℃	>0	-3,-5
Vertical pressure/kPa	400,600,800,1 000	200,400,600,800

The sample is 20 cm in height and divided into five layers to compact. Before the test, the subgrade filling was dried and passed through 1 mm sieve. According to the weight of wet soil required for each layer, soil samples were mixed evenly and added to the shear box. The axial loading system of the large direct shear apparatus was used to carry out the static compaction, and the load was increased gradually. When the soil sample was compacted to the target thickness, the surface was made to be irregular and the next layer was added to compact. Meanwhile, two temperature sensors were separately arranged in the position which was 2 cm distant from the shear plane. After the preparation of soil samples, the refrigeration system was opened to cool and freeze the soil samples. The shear test began when the monitoring temperature met the requirement.

2 Test results

2.1 Characteristics of stress τ and displacement s

At different temperatures, the relationships between shear stress and shear displacement of subgrade filling with optimum moisture content are shown in Fig. 3.

From Fig. 3, it can be seen that shear stress changes obviously and increases gradually when the vertical stress varies from 200 to 800 kPa at the

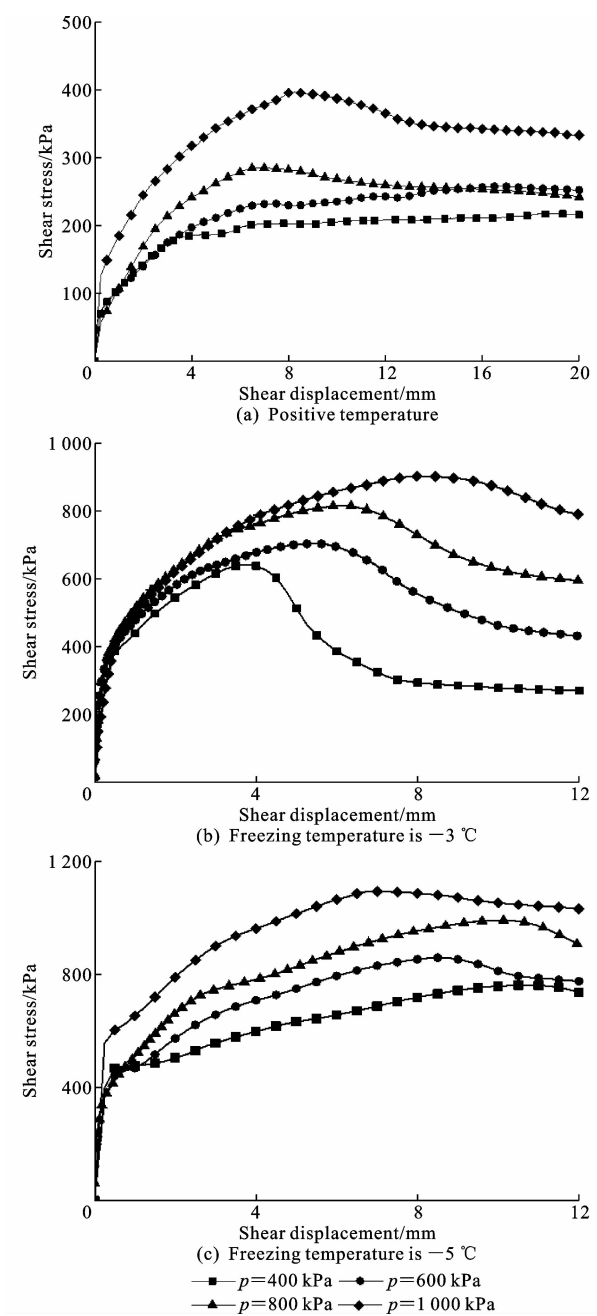


Fig. 3 Relationship curves between stress and displacement

图 3 剪应力-剪切位移关系曲线

same temperature. As shown in Tab. 2, under the same normal stress, the shear strength of soil at negative temperature is clearly larger than that at positive temperature. For example, when the subgrade filling temperature is decreased from positive temperature to $-3\text{ }^{\circ}\text{C}$ and the vertical pressure is 400 kPa, the shear strength increases significantly from 182 to 703 kPa. The reason is that there are less unfrozen water and more ice crystal, which leads to the enhancement of binding between ice

and soil particles as well as the increase of shear strength. The shear strength of sample at lower cooling temperature is larger than that at higher freezing temperature. It can be seen from Tab. 2, the shear strength of subgrade filling has increased by more than 100 kPa under the same vertical pressure when the cooling temperature decreased from $-3\text{ }^{\circ}\text{C}$ to $-5\text{ }^{\circ}\text{C}$. This is because the more ice crystal, the less unfrozen water is, and the lower cooling temperature is. The ice, in voids of soil, with high strength bears a certain shear stress and the binding between ice and soil particles is more intensive. Therefore, the shear strength improves^[16].

Tab. 2 Maximum strengths of soils with different temperatures and vertical pressures
表 2 不同温度、不同垂直压力条件下峰值强度

Temperature/ $^{\circ}\text{C}$	Vertical pressure/kPa				
	200	400	600	800	1 000
>0		182	259	310	396
-3	641	703	814	900	
-5	763	860	993	1 111	

(2) Under the conditions of different temperatures and vertical stress, the τ - s relationship of soil, from direct shear tests, is basically the same, and generally, it is divided into 3 stages^[17]:

① Consolidation stage. It is also known as elastic segment, in which an approximately linear relationship is between τ and s . During early stage of loading of shear, the τ - s relationship curves gradually bend from approximate linearity, and by this time, the shear stress inside soil generated by the loading is smaller than shear strength of soil. The deformation of soil is mainly resulted from the compaction of shear stress, namely porosity reduced inside soil.

② Partial shear stage. It is also known as strain hardening segment. During this stage, there are recoverable elastic deformation and plastic deformation which are obviously unrecoverable. With the increase of shear stress, the gradient of τ - s curves $d\tau/ds$ decreases gradually, meanwhile, the shear strength augments slowly, and then reaches the peak strength gradually. During this stage, the obvious plastic deformation of soil occurs, which

means that the soil begins to yield. However, the plastic strain increases the resistance against the deformation of soil, which results in the yield strength rising with the shear stress increasing. During this stage, the compaction of soil consists of the dislocating, rolling and breaking of soil particles, and the shear stress fluctuates significantly with the increase of shear displacement^[18].

③ Failure stage. It is also called strain softening. During this stage, when τ rises at the maximum or the shear deformation accumulates to a certain value, the shear stress has a sudden fall or decreases gradually, but at the same time, because the shear deformation continues to increase rapidly. It means that the shear failure plane has been formed inside soil and the resistance against plane deformation is mainly derived from the friction force among particles.

2.2 Internal friction angle φ and cohesion c

According to the maximum shear strengths of soils at different temperatures T , Fig. 4 shows the relations between τ and vertical pressure p . It can be seen that there is a better linear correlation between vertical pressure and shear strength. With the increase of vertical pressure, the shear strength becomes larger. The correlation coefficients of fitting curves are 0.991 6 at positive temperature, 0.989 5 at the freezing temperature of $-3\text{ }^{\circ}\text{C}$ and 0.996 5 at the freezing temperature of $-5\text{ }^{\circ}\text{C}$, respectively.

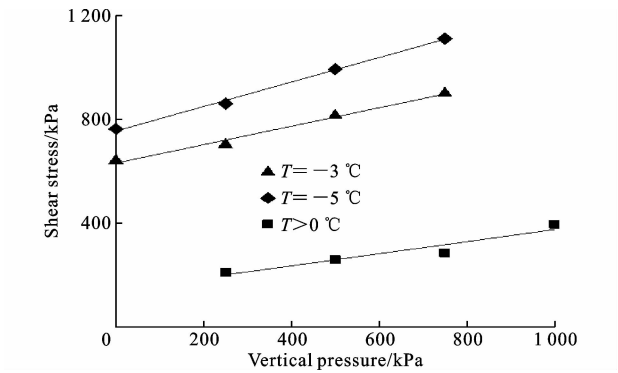


Fig. 4 Fitting curves of peak values of shear strengths

图 4 路基填料抗剪峰值强度拟合曲线

According to the results of the fitting curves, cohesions c and internal friction angles φ are 43.7 kPa

and 19.4°, 542 kPa and 26.5°, 637.5 kPa and 33.8° when the cooling temperatures are positive temperature, −3 °C and −5 °C respectively (Tab. 3). That is to say, the lower the cooling temperatures are, the larger φ and c are, because there is less unfrozen water in soil with lower cooling temperature, and the unfrozen water has a direct effect on the binding between ice and soil particles. The key factor of frozen soil with high cohesion is the stronger binding. The internal friction angle of subgrade filling is determined by the size of soil particles, the surface roughness as well as the binding between particles. With the lower cooling temperature, the binding between ice and soil particles will enhance, which leads to an increase of internal friction angle finally.

Tab. 3 Internal friction angle φ and cohesion c

表 3 路基填料的内摩擦角 φ 和黏聚力 c

Parameter	Temperature/°C	Cohesion c /kPa	Internal friction angle φ / (°)
Parameter value	>0	43.7	19.4
	−3	542.0	26.5
	−5	637.5	33.8

2.3 Shear dilatancy

The relationships between shear dilatancy and shear displacement, which indicate the frozen soil at negative temperature, are shown in Fig. 5. And the amount of shear dilatancy was measured by the data acquisition system. Unfrozen soil at positive temperature was not listed here because the obvious shear dilatancy was not observed during tests.

Based on the results of the test, the frozen subgrade filling obviously shows shear dilatancy, and its development trend is positively related to the shear displacement, namely, the shear dilatancy increases with the increase of shear displacement.

Tab. 4 shows the values of shear dilatancy when the shear displacement of subgrade filling is 12 mm at different temperatures. When the temperature is −3 °C, with the increase of vertical pressure, the shear dilatancies are 5.26, 4.86, 3.60, 2.05 mm respectively. While the freezing temperature is −5 °C, they are 4.93, 4.53, 3.56 and 2.02 mm respectively. Therefore, at the same

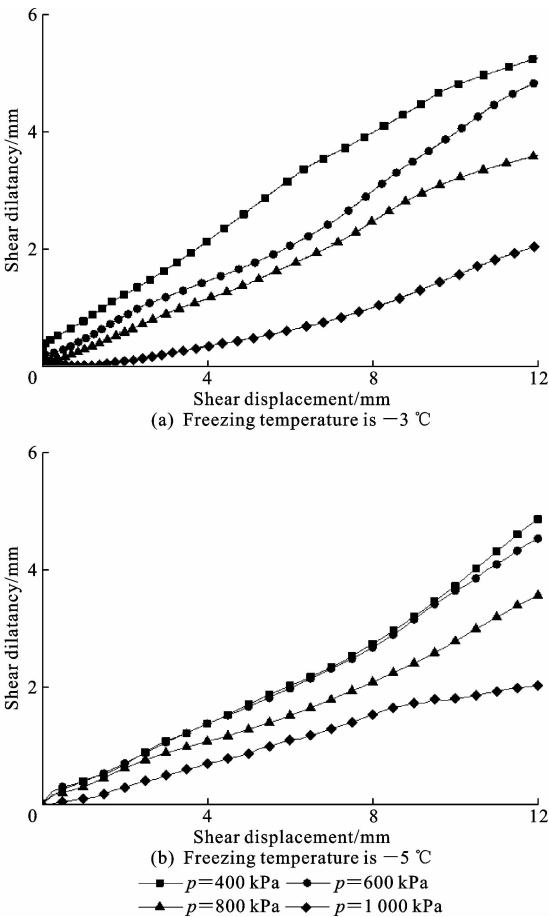


Fig. 5 Relationship curves between shear dilatancy and shear displacement

图 5 剪胀量-剪切位移关系曲线

cooling temperature, the shear dilatancy is negatively correlated with the vertical pressure. In other words, with the increase of vertical pressure, the shear dilatancy decreases. However, it has no obvious change at negative temperatures and is almost equal under the same vertical pressure.

Tab. 4 Shear dilatancies under different freezing temperatures

表 4 不同冻结温度下路基填料剪胀量 mm

Temperature/°C	Shear dilatancies under different vertical pressures(kPa)			
	200	400	600	800
−3	5.26	4.86	3.60	2.05
−5	4.93	4.53	3.56	2.02

3 Conclusions

(1) Under the same vertical pressure, the cohesion of subgrade filling at −3 °C is over 500 kPa more than that at positive temperature, and is 95.5 kPa less than that at −5 °C. With the tem-

perature decreasing from positive temperature to -5°C , the internal friction angle increases from 19.6° to 33.8° . The shear strength of subgrade filling of Shenshuo Railway is significantly affected by cooling temperature.

(2) The subgrade filling in frozen state shows obvious shear dilatancy. At negative temperature, with the increase of vertical pressure, the shear dilatancy becomes a decreasing trend. However, it has no obvious change and is almost equal with the cooling temperature.

(3) There are still some problems which need to be further studied. In the future, it is necessary to study the improvement of mechanical properties of subgrade filling, such as mixing cement, changing gradation and so on.

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