

# Experimental Research on Frost Heaving Characteristics of Coarse Grained Soil Filler of High Speed Railway Subgrade in Cold Region

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**Abstract.** The Haerbing-dalian high-speed railway subgrade packing is as the research object. Influence factors of frost damage are analyzed, such as packing soil(size composition,Mineral composition,compactness),moisture,temperature external load and salt content, etc. Through characteristic tests of frost heaving, research on Influence of subgrade frost heave with or without the condition of train load conditions was made, including content of fine grained soil, water-holding capacity, packing grading, permeability coefficient, freezing time, condition of water replenishing, etc. Results have shown that:Group A,group B and graded gravel packing moisture rate are between 5.5% ~7.9%;With the reduction of fine aggregate under gravel level,rate of filler frost heave gradually decreases,but frost heave still exists under the condition of low temperature even if fines content is small;The overlying pressure plays a restraining role to the frost heaving of packing;Freezing rate has a great impact on the rate of frost heaving;When cooling rate of 0.2°C/h is 1.77 times faster than that of 1.0°C/h,frost heave quantity increased significantly;When the permeability coefficient is more than  $10^{-3}$ , soil frost heave coefficient is less than 1, this kind of soil belongs to weak frost heaving soil.

## Introduction

Subgrade differential settlement caused by seasonal frost heave and thawing is one of the important reasons that affect the safe operation of high speed railway train in cold region [1]. Frozen soil is a kind of temperature-sensitive and changeful geological body, is extremely sensitive to hydrology, surface conditions and climate change. Subgrade frost heave is formed by in-situ water freezing and water in not frozen area migrating and accumulating to the freezing front and crystallizing into ice lens [2,3,4,5].

With the rapid development of China's economy, a large number of high speed railway will be built in cold region, such as Chang-ji, Ha-da, Ha-qi, Shen-dan, Pan-ying, Lan-xin, etc. High speed railway is very strict on subgrade deformation, and excessive frost heave deformation will affect the safety of train operation, comfort. According to the current statistics, Haerbing-dalian high-speed railway stretches approximately 237 km range, there are more than 20000 sections of frost heave, the largest frost heave height of 80 mm, seriously affected the safety of the high-speed railway operation. Effect factors of subgrade frost heaving are complicated, including hydrology, climate, soil features and construction control, etc. These makes the subgrade frost heave deformation uncertain [6,7,8]. The researches on the mechanism of the frost heaving characteristics and water-holding performance, especially in high speed railway bed coarse aggregate, such as content of fines, water-holding performance, permeability coefficient, external load, freezing time, filling water conditions, are insufficient. In order to ensure the comfort and security of high speed railway operation in cold region, high speed railway subgrade frost heaving characteristics experimental study in cold region should be researched and solved urgently.

## Genetic Analysis of Subgrade Frost Damage

Frost heave refers to the soil freezing process, in which the soil moisture freezes into ice, then ice layer, ice lens, polycrystal ice crystals and other forms of ice body, causing the relative displacement between

the soil particles and the phenomenon of soil volume dilation of different level. Practice shows that, when the volume increment caused by soil moisture freezing exceeds the original pore volume, soil frost heave occurs. Many factors affect the soil frost heave, including soil, water, temperature, salinity, external load, etc. are The main factors that cause soil frost heave are soil texture, water and temperature [9,10]

## Soil Texture

**Composition of Particle Size.** The composition of particle size refers to the shape and size of solid particles and the interaction relationship between them. Soil particle size has a significant impact on frost heave, different soil particle size reflects the differences of force field of grain surface, directly affects the moisture migration ability in the process of soil freezing, and leads to the different characteristics of frost heave deformation.

When particle size is greater than 0.1 mm (coarse particle), the function of combination with water is weak, moisture won't move to the freezing front, drainage will happen under the action of gravity, soil frost heave won't occur. With the decrease of the soil particle size, the possibility of frost heave increases. When particle size is between 0.1~0.05mm, frost heave would happen in the soil. Frost heave reaches the maximum amount when particle size is between 0.05~0.002mm. When particle size is less than 0.002 mm, namely the clay particles, migration quantity of soil moisture reduces due to the increase of particle dispersibility, frost heave also reduces correspondingly.

**The Soil Compactness.** As the compactness of soil increases, the porosity of the soil will decrease. When soil with small compactness freezes, ice will swell fully in pore space, and does not cause the separation between soil particles. Intensity of soil frost heave is negligible. When the soil compactness increases to a certain value, the soil pore is minimum, and reaches the best particle reunion condition. Soil compactness provides the most favorable condition for film mechanism of moisture migration, soil frost heave reaches the maximum intensity. When soil compactness exceeds the certain value, free water will be reduced gradually as the soil compactness increases, accelerating the soil freezing. Instead, the intensity of soil frost heave would decrease. Tests show that the certain value is close to 18kN/m<sup>3</sup>.

**The Mineral Composition of Soil.** Soil particles are composed of solid mineral grains. Intensity order of frost heave with the different mineral composition of cohesive soil is: kaolinite > silty soil > clay soil > sand > montmorillonite. Therefore, kaolinite-dominated cohesive soil has the maximum frozen-heave character, it is not easy to compact when water content is large during construction. Coarse grain soil like gravel and sand soil show no evidence of frost heave affected by mineral composition, while the content of fines and composition in the coarse grained soil play a decisive role in frost heave.

## The Moisture

Soil moisture content is one of the basic causes of subgrade frost heaving. Soil body can be divided into the closed system and the open system. In addition to the moisture in soil itself, water would supply from atmospheric precipitation, groundwater and return water caused by different kinds of hydraulic projects. So after freezing, water content within the scope of the frozen soil increases significantly, causing a bigger frost-heave amount as well. In a closed system, the frost heave is mainly caused by the freezing and the migration of water. Since there is no external water supply, water content increases significantly only in the upper soil layer (fine grain content is higher, generally above the 1/2 ~ 1/3 maximum frozen depth section), water content decreases in the lower soil, the amount of frost-heave is relatively small.

## The Temperature

The temperature is another important factor that causes soil frost heave. In general, the longer the freezing time lasts, the lower the temperature, the greater the soil frost heave. The influence of the temperature includes freezing index and freezing rate. Under the same condition, the subgrade frost goes with the freezing index. If the cooling is fast in winter, then the freezing will speed up, and reach to the maximum frozen soil base quickly. The moisture is too late to migrate fully, the amount of frost heave is small. If the winter is of frequent alternation in temperature, the freezing speed is slow, the moisture would get full migration, the amount of frost heave increases significantly.

## The External Load

To increase the external load has the significantly inhibitory effect for soil frost. External additional stress increases the contact stress between soil particles, reducing the ice freezing point and initial water content, moisture migration process has been restricted. When the load increases to a certain value, the frozen face isn't bibulous, interrupts the moisture migration from none-frozen zone to freeze front zone, Soil frost heave stops, the load at this time is called the suspend pressure. But if the temperature drops, frost heave may still occur, usually the upper load of subgrade and traffic loads are very difficult to reach the suspend pressure.

## The Salinity

Salinity in the soil affects the freezing temperature, frozen water content and the osmotic pressure of water through the soil. With the increase of concentration of salt solution, the freezing point of soil drops, soil frost heave amount decreases, and when the concentration of salt solution reaches a certain value, frost heaving of soil becomes very small. Tests show that salt solution concentration of silt, sandy loam, mild clay is greater than 2%, 8% and 10% respectively, the frost heaving will not take place. To make use of this feature, it is very effective to improve the subgrade and prevent subgrade frost heave by adopting the method of artificial salinization.

## Packing Characteristic Test of Frost Heave

This test intends to analyze the characteristics of soil frost heave in terms of water content, soil compaction degree, grain content, the permeability coefficient, the load effect and so on, study the change rule of soil frost heave caused by above factors, then study the influence of different factors on the packing frost heaving, and provides the basis for frost heave rail structure design and relevant parameter design in cold region.

## Penetration Test

Permeability coefficient  $K$  is the comprehensive indicator to reflect the soil infiltration capacity, mainly depends on the shape, size, uneven coefficient of soil particles and the viscosity of water. This experiment adopts the penetration test of falling head permeameter, the sample 61.6 mm in diameter, high 40 mm. Soil samples are obtained from a total of 49 groups for penetration test, and have unearthed diagram of the coefficient of permeability vs fine particle content, as shown in Fig. 1.

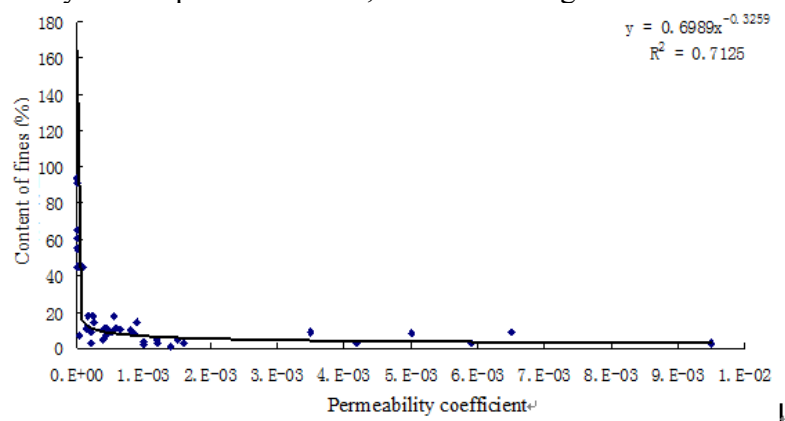


Fig. 1 Curve of Permeability Coefficient VS Content of Fines

Regression analysis was carried out on the content of fines and permeability coefficient, both have a certain correlation, as shown in Eq. 1:

$$y = 0.6989 \times k^{-0.3259} \quad (1)$$

( $y$ : content of fines,  $k$ : the permeability coefficient of soil). When the coefficient of permeability is greater than  $1 \times 10^{-3}$ , content of fines is less than 10%.

## Test of Water-holding Capacity

Water is one of the main factors that cause soil frost heave, low temperature will cause soil frost heave if the infiltration rain cannot discharge in time in late autumn and early winter. Therefore, the research of soil water-holding performance that soil moisture changes over time can provide qualitative evaluation on the performance of the frost heave of soil.

The soil sample was immersed in water and completely saturated for test of water-holding capacity, then removed from the water. Changes of soil moisture over time under the natural condition are tested, as shown in Fig. 2.



Fig. 2 Test of Water-holding Capacity

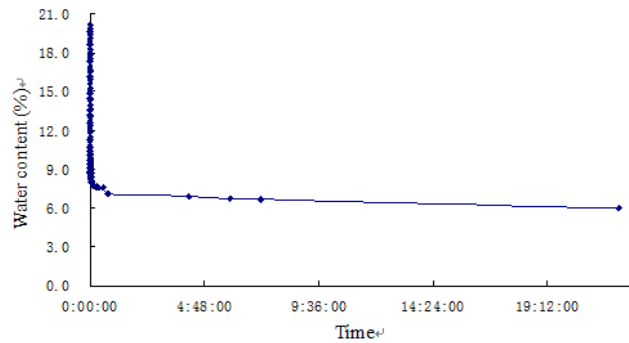
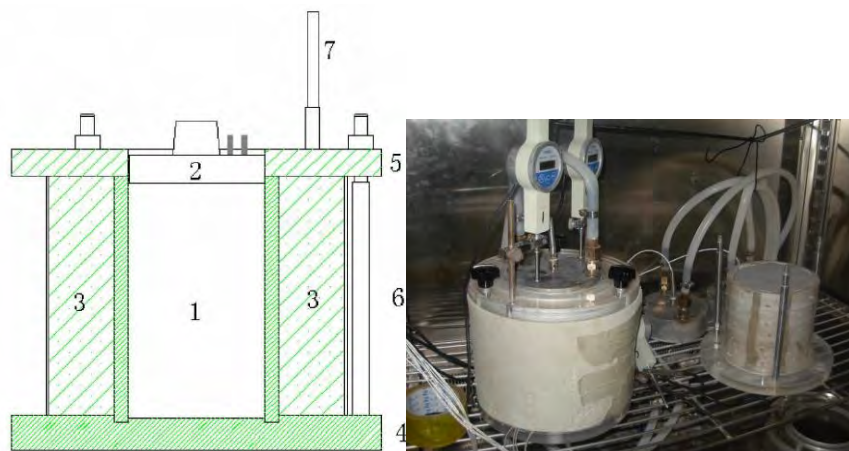


Fig. 3 Curve of Water Content VS Time

From figure 3 we can see that, for coarse grained soil with small fines content after 24 hours of test with full of water, soil moisture in soil sample can return to the initial moisture content around (the optimum water content).

## Frost Heaving Test

Test device is mainly composed of specimen box, incubator, cold bath, the temperature control system, the temperature monitoring system, water system and deformation monitoring system. Test specimen box is 15 cm in diameter and 15 cm high. At first, soil sample is configured with water content by the regulation, then stratified into packaged specimen box in a certain compactness for frost heave test. The sample is divided into 5 layers along the height direction of the box, each layer is 3 cm, layers can move freely when the frost heave deformation happens, effectively eliminating the influence of surface effects of frost heave. Polystyrene materials were used for thermal insulation around the sample box. In the top displacement sensor was mounted to test frost heave deformation. Temperature sensor was embedded in internal soil to collect sample temperature automatically, the test adopts the unidirectional freezing method, as shown in Fig. 4.



1- Sample; 2- Cold Bath; 3- Thermal Insulation Material; 4- Floor; 5- Roof; 6 - Fixed Rod; 7 - Displacement Meter Fixed Link

Fig. 4 Frost Heaving Test Device

**The Impact Test of Fines Content.** Frost heave won't happen or frost heaving amount is small in coarse grained soil when content of silt, clay particle under 0.05 mm (or 0.075 mm) is very small. However, as the fines content increases, the frost heave of soil will gradually grow. This test carried on 12 groups of coarse grained soil with similar moisture content for frost heave test, the test result is presented in Fig. 5.

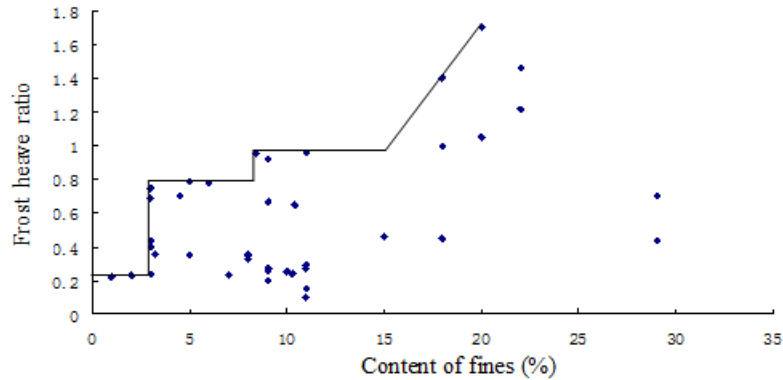


Fig. 5 Curve of Content of Fines VS Frost Heave Ratio

It can be seen from figure 5 that with the increase of the content of fines, frost heave of coarse grained soil gradually increases. When the fines content is lower than 3%, soil frost heave rate is at around 0.2, when the fines content is lower than 15%, the soil frost heave rate is less than 1, this kind of soil belongs to the weak frost heaving soil. With the increase of the content of fine grained soil, frost heave susceptibility of soil frost would increase significantly when fines content is more than 15%. So certain measures should be taken for prevention in the roadbed design, even if the fines content is very low (less than 3%).

**The Impact Test of Water-saturation.** By comparing the soil frost heave under saturation and close condition, we can compare the soil frost heave sensitivity, and study the influence of fines content on the frost heave sensitivity of soil packing. Frost heaving relationship under saturation and close condition is obtained through indoor test, as shown in Fig. 6.

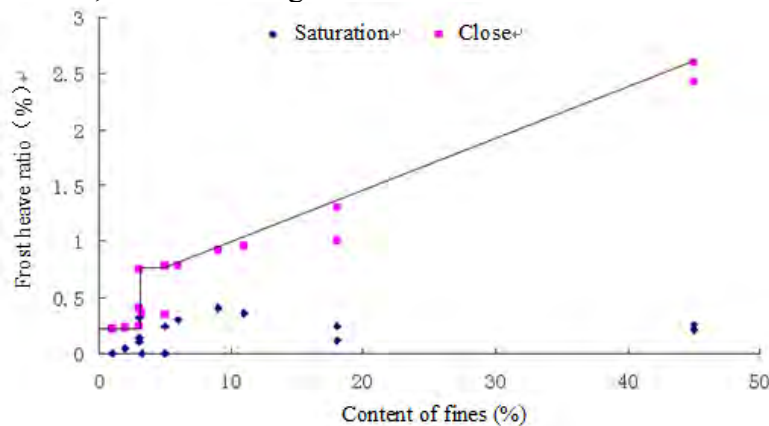


Fig. 6 Curve of Content of Fines Vs Frost Heave Ratio under Saturation and Close

The figure 6 shows that with the increase of fines content less than 0.075 mm in particle size, effect of water on packing frost heave increases. When the fines content is lower than 5%, changes of frost heaving isn't obvious under saturation and close condition, this soil belongs to the no-sensitivity frost heaving soil. When the fines content is more than 5%, frost heaving in the water-saturation system increases gradually as the fines content grows.

**The Impact Test of Load.** Adding additional external load upon soil has certain inhibitory effects on soil frost heave. The impact of stress on the soil frost heave is essentially reflected in the following two aspects: external pressure increases while the soil freezing point drops; water redistribution in the soil

caused by external pressure. Tests of 4 soil samples are adopted by loading upon soil, as shown in Fig. 7, the test results is shown in Fig. 8.

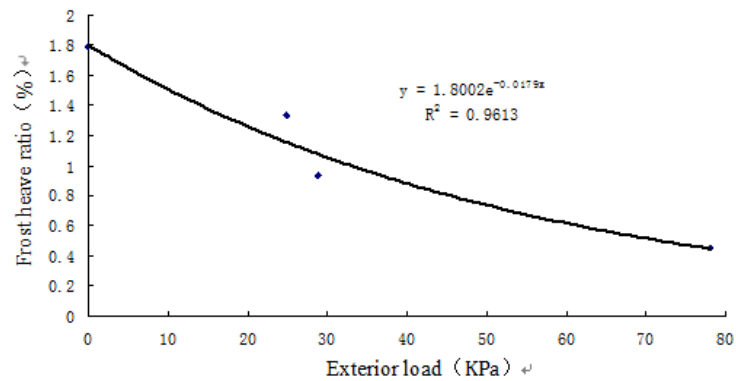


Fig. 7 Investigation of Loading Device Fig. 8 Curve of Exterior Load VS Frost Heave Ratio

The figure 8 shows that there is exponential relationship between the overlying load and the soil frost heave rate, with the increase of overlying load, soil frost heave rate reduces gradually. To eliminate the soil frost heaving takes very huge external loads, usually overlying load on railway roadbed cannot eliminate the influence of soil frost heaving.

**The Impact Test of Freezing Rate.** Throughout the winter, typical temperature in northeast China is under the type of concave, experiences three processes, namely drop stage in temperature, low temperature fluctuation stage and temperature rising stage. Take the winter cooling rate of Haerbing-dalian railway into consideration, areas of Dalian and Yingkou are relatively slow in cooling rate, while north of Shenyang area is relatively fast.

Relationship between average cooling rate and the average frost heave along the subgrade bed is shown in Fig. 9, 10. Results show that there exists a certain correlation, generally, the smaller the average cooling rate is, the greater the frost heaving would be.

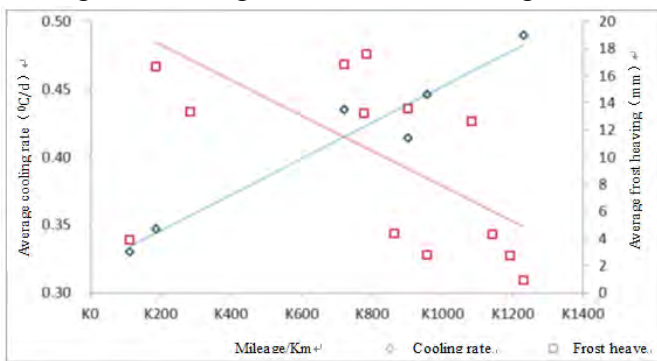


Fig. 9 Curve of Accumulated Negative Temperature Index VS Frost Heave

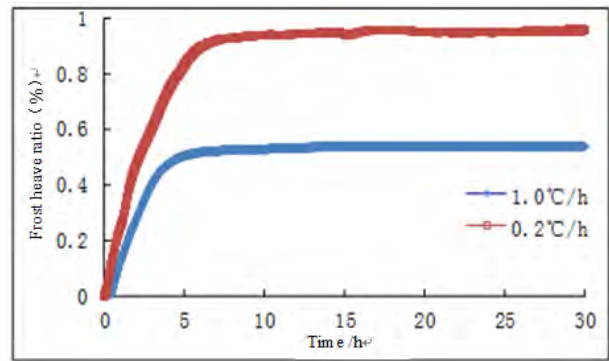


Fig. 10 Curve of Frost Heave Ratio VS Time at Different Cooling Rates

Unidirectional freezing tests in the same condition show that freezing rate has a great impact on frost heave deformation. The temperature drops from top to bottom, soil moisture moves to the top in the early, and leads to obvious frost heaving, frost heave is relatively small later. When freezing rate is slow, more water moisture moves to the upper soil, causing larger deformation. Graded crushed stones with 5% moisture content are tested for frost heaving at the cooling rate of 1.0°C/h and 0.2°C/h. Test results show that the amount of frost heave at the cooling rate of 0.2°C/h is much bigger than that at 1.0°C/h, frost heave rate of soil at the cooling rate of 0.2°C/h is 1.77 times faster than that at 1.0°C/h.

**Frost Heave Tests of Graded Crushed Stone.** In order to study the frost heaving influence of fines content on graded crushed stone packing at surface layer of subgrade bed, 35 groups of graded crushed stones with different fines content are tested for frost heaving, relations of the two are shown in Fig. 11.



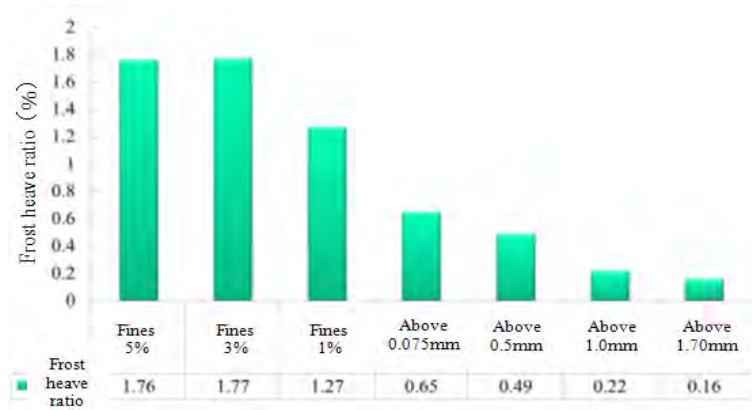


Fig. 11 Influence Content of Fines to Frost Heave of Graded Broken Stone

It can be seen in figure 11 that with the decrease of fine aggregate under gravel size, frost heave rate of filler gradually decreases.

**The Impact Test of Permeability Coefficient.** According to the survey, the rainy season along the Haerbing-dalian high speed railway is mainly centralized in June, July and August. Rainwater can permeate through the subgrade basically if waterproof measure is not taken. When the permeability coefficient is big, water moisture will discharge out of the subgrade quickly, make the water content in soil low, and is not easy to migrate under low temperature. It is conducive to meet the requirement of subgrade frost heaving prevention. 24 groups of different soil samples are tested for permeation and frost heave, the relationship between permeability coefficient and frost heave is shown in Fig. 12. By the graph, when the permeability coefficient is more than  $10^{-3}$ , the frost heave coefficient is less than 1, this belongs to the weak frost heaving soil.

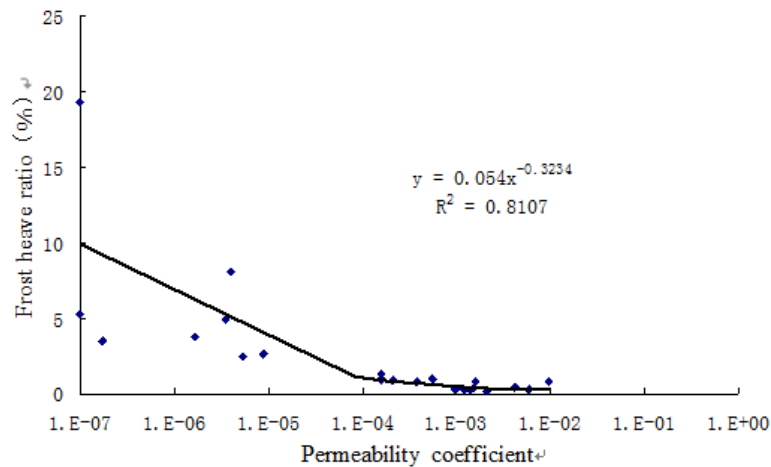


Fig. 12 Curve of Permeability Coefficient VS Frost Heave Ratio

Regression analysis is made between permeability coefficient and rate of frost heave, there exists good correlation, as shown in Eq. 2:

$$\eta = 0.054k^{-0.3234} \quad (2)$$

( $\eta$ :frost heave coefficient;  $k$ :permeability coefficient).

## Conclusions

This paper takes the Haerbing-dalian high-speed railway subgrade packing as the research object, analyzes the influence factors of subgrade frost damage. Through indoor frost heaving characteristics test, study is made to analyze the impact characteristics of subgrade frost heaving, including fines content,

water-holding capacity, permeability coefficient, external load, freezing time, condition of water replenishing, etc. The main conclusions are as follows:

(1) Tests of water holdup show that, The natural moisture rate of Group A, group B and graded crushed stone packing are between 5.5% ~ 7.9%.

(2) Tests of different graded packing show that, with the decrease of fine aggregate under gravel size, frost heave rate of filler gradually decreases. But, a certain amount of frost heaving still exists in low temperature, even if the fines content is small.

(3) The impact tests of external load show that, the external load plays a certain inhibitory role for soil frost.

(4) Unidirectional freezing tests in the same condition show that freezing rate has a great impact on frost heave deformation. Test results show that the amount of frost heave at the cooling rate of 0.2 °C/h is much bigger than that at 1.0 °C/h, frost heave rate of soil at the cooling rate of 0.2 °C/h is 1.77 times faster than that at 1.0 °C/h.

(5) The results of permeability coefficient versus frost heaving test show that, when the coefficient of permeability is greater than  $1 \times 10^{-3}$ , soil frost heave coefficient is less than 1, this soil belongs to the weak frost heave soil.

## Acknowledgement

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