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Research Paper

Experimental study on the water-heat-vapor behavior in a freezing coarse-grained soil

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HIGHLIGHTS

- The frost susceptibility of coarse-grained soil considering "pot" effect is investigated.
- The influence of fines and initial water content on the moisture migration and frost susceptibility is studied.
- The effect of vapor transfer and external water supply on the frost heave of coarse-grained soil is evaluated.

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ABSTRACT

A series of one-side freezing experiments of a coarse-grained soil with different contents of clayey loess were conducted in an open system with no-pressure water supply, to evaluate the influence of fines content and initial water content on the moisture migration and frost susceptibility of the coarse-grained soil, and to investigate the frost heave mechanism of coarse-grained soil under consideration of "pot" effect. The experimental results show that a thin ice layer appears in the cold end boundary by simulating the impervious cover, which is an important reason for the frost heave of coarse-grained soil. The frost susceptibility of the coarse-grained soil is influenced by fines content significantly, and the amount of frost heaving and frost heave ratio of soil samples increase linearly with the increase of fines content. The influence of external water on the frost susceptibility of the coarse-grained soil could not be neglected, and with the increase of fines content, the external water supply will increase. Meanwhile, with the increase of initial water content, the frost heave of coarse-grained soil increases. The start time of water intake is delayed, and it would be enlarged with the decreases of fines content and initial water content. Besides, it is also found that in the case of lower moisture content, the effect of vapor transfer on the frost heave of coarse-grained soil will become more obvious.

1. Introduction

Frozen soil is a kind of soil or rock containing ice below 0 °C, and 53.5% of China's land surface is seasonally frozen regions [1]. Frost heave in winter and thaw settlement in spring are the most common mechanisms causing the damages of road pavement structure in seasonally frozen ground, and engineers engaged in road construction usually use the non-frost-susceptible base materials to minimize the frost heave and thaw settlement deformations of pavement structure. The Haerbin-Dalian Passenger Dedicated Line (HDPDL) passes across a typical middle-deep seasonally frozen ground regions in Northeast China, and a series of measures (such as insulation, frost-resistant berm, isolation and drainage measures) were taken to prevent and solve these problems in the construction process, e.g. A/B group fills (unsusceptible material to frost heave) as subgrade fillings. However, the deformations still existed, and even exceeded the standard limit [2,3]. Some research was carried out on these problems [4].

In order to control the deformation of high-speed railway subgrade and to meet the requirement of standard limit, the content of fine particles is required less than 5% [5]. It has been found that fine particles have a significant influence on frost heave susceptibility of subgrade fillings. Konrad and Lemieux [6] found that the frost susceptibility of well-graded crushed aggregates increases with increasing fines content. Zhang et al. [7] found that water

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content is the most important factor causing frost heave of coarse-grained soil, but the influence of mud content is limited. Konrad [8] conducted ramped-freezing tests on base-course materials with fines content less than 7% with an access to an external water resource, and it is found that the frost heave was relatively small, but significant water intake occurred in all samples. Wang et al. [9] studied the frost susceptibility and strength properties of coarse-grained soil by means of frost heaving tests and static triaxial tests, and found the frost heave ratio increased gradually and the frost susceptibility of fines weakened the shear strength of coarse-grained soil with the increase of fines content. Although the effect of fines content on frost heave was taken into account in the above research results, the influence of vapor migration on water content is neglected. In cold and arid climate regions, the ground surface, far from the groundwater, is unsaturated and moisture evaporation mostly occurs in the surface soil. Moisture migration is driven by a temperature gradient in the ground and is prevented by an impervious layer, leading to moisture accumulation under it and even reaching to full saturation. This phenomenon is called as the "pot" effect [10]. When the temperature near the ground surface drops below the frost point, vapor and liquid water under the impervious cover will be changed into ice through desublimation and freezing. The formation of ice will further reduce vapor density and increase the matric suction, which in turn accelerates the vapor transfer in the ground. Some researchers had carried out the study of vapor migration in the condition of thawed soil, and found that the movement of vapor is also the main pattern of moisture transfer in soil at a certain extent [11–13]. Especially under the isothermal conditions, the factors such as soil, water content gradient and water content have significant effects on the migration of vapor [14]. Dobchuk, et al. [15] found that the main factors affecting the migration of water vapor are dry density, porosity and diffusion coefficient. For frozen soil, there are still obvious water vapor transport phenomena [16,17] in unsaturated soils under the gradients of water content or temperature gradients. Eigenbrod et al. [18] found that the amount of water vapor transport of soils containing fine granular soils was obviously higher than that of pure coarse-grained soils. Wang et al. [19] conducted the moisture migration test of freezing unsaturated loess under a closed condition. When the initial water content of the soil is small, the grill blocking liquid water has little effect on the moisture migration induced by freezing, and the moisture migration to freezing front was mainly carried out by vapor. When the initial water content is large, moisture migration is mainly conducted by liquid water transfer. Zhang et al. [20] worked out the moisture migration experiments under different water contents and different boundary temperatures, and found that water content in the upper position of the sample increases under a upward temperature gradients at the frozen and/or unfrozen states, and the increment of water content will be larger if the soil is subjected to freezing.

As shown from the above research results, the fines content and water content are the main factors influencing the frost susceptibility of a coarse-grained soil, and water vapor at a certain extent determines the quantity of moisture migration. However, the above researches have been carried out in one aspect, and the influence of vapor transfer on frost heave has not been considered. At present, less attention has been paid to the effect of vapor migration and fines content on the frost susceptibility of a coarse-grained soil, and experimental studies have hardly been conducted. Therefore, in this paper, a series of one-side freezing experiments of a coarse-grained soil with different contents of clayey loess were conducted in an open system with no-pressure water supply, to study the influence of fines content and initial water content on moisture migration and frost susceptibility of the coarse-grained soil, and to investigate the frost heave mechanism of the coarse-grained soil under consideration of "pot" effect.

2. Experiment

2.1. Experiment equipment

Experiments were carried out in the freezing and thawing test chamber of State Key Laboratory of Frozen Soil Engineering, which mainly includes temperature control system, water supply system and data acquisition system. Temperature control system is composed of the controlling temperature of top plate, bottom plate, and test box and visualization software. Controlled liquid, circulated through the top and bottom plates of the test chamber, is alcohol, which could be set from −40 °C to +60 °C with an accuracy of ±0.5 °C. Operating temperature of the test chamber box ranges from −35 °C to +40 °C. The no-pressure water supplement system is composed of a Mariotte flask connected with the bottom plate through plastic tube, and the amount of water intake is determined by the difference among the water level. The data acquisition system is composed of DT80, and data of temperature and displacement are automatically collected every 20 min.

2.2. Experiment design

The fines soil used in these experiments is clayey loess taken from the Harbin Dalian high-speed railway in Northeast China, and its physical parameters are given in Table 1. The dried clayey loess was crushed and then sieved over 0.075 mm, and a certain amount of sieved soil was mixed with graded crushed stones. Two groups of freezing tests were conducted. One was to study the influence of fines content on the frost susceptibility of coarse-grained soil with four samples, labelled I–IV (shown in Fig. 2). The other was to study the influence of initial water content on the frost susceptibility of coarse-grained soil with three samples, labelled IV–VI, and the sample IV was jointly used in the two test groups. In this paper, the cumulative curve of coarse-grained soil (sample IV) containing 5% fines by weight is illustrated in Fig. 1. The non-uniformity coefficient of the cumulative curve of sample IV is 15.78, and the coefficient of curvature is 2.63, belonging to a well graded soil. All the samples were prepared in advance, and sealed in a plastic bag for 24 h to ensure adequate moisture redistribution. The test tube is made of organic glass with 30 cm in height, 19.8 cm in inner diameter and 2 cm in thickness. The coarse-grained soil was divided into four equal parts, and each part was compacted into the test tube with a hammer to the target height with the dry density of 2.087 g/cm^3. In order to simulate the impervious cover in field environment, once the final height of 200 mm was obtained, a thin plastic film was covered at the top surface of the sample (shown in Fig. 2a) to seal and prevent moisture evaporation during freezing (shown in Fig. 2b). The apparatus was instrumented with 9 thermistors at 2 cm intervals along the vertical direction to monitor the soil temperatures at different depths and 1 displacement sensor at the top of the sample to

Table 1
Physical parameters of clayey loess.

Soil	Initial water content/%	Natural dry density/g/cm^3	Liquid limit/%	Plastic limit/%	Plasticity index	Types
clayey loess	20.64	1.67	45	25	20	clay