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An experimental study on the frost heave properties of coarse grained soils

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ABSTRACT

We investigated the impact of fines content on frost heave and compaction in subgrade construction materials, in order to determine the optimum fines content of coarse-grained soils (CGS) required to achieve reduced frost susceptibility and efficient compaction simultaneously. We conducted laboratory freezing tests simulating thermal conditions in the field, and compared open and closed systems. We studied 47 samples with different fines content, dry density, overburden pressure, and water supply (open or closed) by compaction tests and frost heave tests. Among other significant effects observed, the freezing temperature decreased gradually with incremental increases in the percent content of fines. Fines content proved to be an important factor influencing the amount of frost heave of CGS. Overburden pressure restrained the amount of frost heave to some extent. The frost heave ratio of CGS samples increased first before reaching the peak value of dry density and then decreased. Overall, our results show that the optimum fines content at which the CGS could be compacted effectively with low frost heave susceptibility was 9%. We also conclude that in the field, it is imperative to employ waterproofing and drainage measures.

Introduction

China ranks third with respect to the expanse of permafrost area in the world. The total area of seasonal frost regions is about 5.14×10^6 km^2, of which 3.67×10^6 km^2 is covered by deep seasonal frozen soil (where the frozen depth is over 2.0 m). Engineering practices and research have shown that much of the railway and highway subgrade damage results from the freeze-thaw processes of deep seasonal frozen soil (Xu et al., 2001). Although deep seasonal frozen soil is known to be a major factor contributing to the instability of subgrades, many high-speed railway (HSR) lines have been built, and more will be built in the near future, in such deep seasonal frost areas in China.

The construction code for HSR subgrade currently specifies that the filling material for HSR subgrade should consist of high-quality coarse-grained soils (CGS), whose fines content should be strictly controlled. Tests have indicated that the frost susceptibility of CGS decreases with the reduction in fines content (Konrad and Lemieux, 2005). However, lower fines content could result in less compaction and therefore greater instability of the subgrade. Obtaining the optimum fines content while simultaneously achieving efficient compaction and with non-frost susceptible (NFS) materials has become an engineering problem for HSR construction in deep seasonal frost areas.

So far, studies on the mechanism of frost heaving and thaw settlement have achieved some success in defining

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the process (e.g. Everett, 1961; Miller, 1972; Chen et al., 1983, Akagawa, 1988; Takeda and Okamura, 1997; Liang et al., 2006). In addition, antifrost subgrade fill—in particular, coarse-grained soils (CGS) and their frost heave properties—have also been investigated. Arenson and Sego (2006) studied the location of unfrozen water during the freezing of CGS using a fluorescent tracer, and found that the location of unfrozen water in CGS differed from that in fine-grained soil. Lai et al. (2012) proposed a new structural embankment whose frost penetration and thaw depth were significantly less than those of a CGS embankment. In terms of the influence of fines content on the frost heave susceptibility of CGS, Konrad (2008), Konrad and Lemieux (2005) concluded that the amount of frost heave in CGS is relatively small when the fines content was less than 7%, and that CGS is susceptible to frost heave when the frost heave ratio is larger than 1%. Frost-susceptibility of well-graded crushed aggregates was found to increase with an incremental increase in fines content and kaolinite fraction (Konrad and Lemieux, 2005). The conclusions of Konrad (2008) and Konrad and Lemieux (2005) have been supported by the results of other studies conducted under similar conditions (e.g. Tester and Gaskin, 1996; Vinson et al., 1986; Ye et al., 2007; Zhang et al., 2007; Xu et al., 2011). Vinson et al. (1986) had previously proposed that the fines particle size was another key influencing factor on the frost heave susceptibility of CGS.

The aforementioned studies showed that fines content is an important factor influencing the frost heave susceptibility of CGS. However, there is no uniform standard to determine the optimum fines content of a given soil, and the differences among the prior results are notable. Therefore, we aimed to seek the optimum fines content that will simultaneously achieve efficient compaction and be non-frost susceptible (NFS). To achieve this objective, the frost heave properties of CGS with different fines contents, dry densities, overburden pressures, and water availability were studied by conducting compaction tests and frost heaving tests.

Experimental setup

The frost heaving test setup was comprised of a sample cell, upside and downside cold plates, NESLAB constant temperature cold baths, a Markov bottle, insulation cotton, temperature and displacement sensors as well as a data acquisition system, as shown in Fig. 1. The sample cell was made of organic glass (the chemical name is methyl methacrylate) with internal dimensions of 30 cm (height) × 20 cm (diameter) and with thickness of 2 cm. The upside and downside cold plates were placed on the upside (cold side) 0and downside (warm side) of the soil sample, respectively. Each cold plate was connected to a NESLAB constant temperature cold bath in order to simulate the unidirectional freezing conditions in the field. The insulation cotton was wrapped around the sample cell to reduce the heat exchange between the sample and the external environment. The temperature of the NESLAB constant-temperature cold bath was controlled with an accuracy of 0.1 °C by using a computer; by means of the cold bath, constant temperature antifreeze was circulated to the upside and downside cold plates to decrease or increase soil sample temperature. For the open system, the water was supplied from the downside of the sample by the Markov bottle in order to simulate ground water supply in the field.

During the frost heave tests, temperature sensors were used for measuring the temperatures inside the sample; 10 platinum resistance thermometer sensors with an accuracy of 0.01 °C were installed in the soil sample through the round hole in the sidewall of the sample cell, as shown in Fig. 1(b). A displacement sensor was installed at the top of the sample, as shown in Fig. 1(b), to measure the amount of surface heave. Its output signal is a voltage value with an accuracy of 0.3%, its reporting range is 2 cm and the accuracy 0.3% is related to the reporting range of the displacement sensor. All the data were collected by a data acquisition system.

Testing program

Material tests

(1) Properties of coarse-grained soils (CGS). The CGS used in this study is natural sedimentary fine round gravel soils, which is the subgrade material for the Harbin–Qiqihar high-speed passenger railway. The physical properties are given in Table 1. The grain size distribution curve of the soil is plotted in Fig. 2. As shown in Fig. 2, Particles with size larger than 2 mm account for 72.61% of total weight, while particles with size smaller than 0.075 mm account for 6.65%.
(2) Properties of fine-grained soil. The fines used in the tests were scalped from the CGS and then added back into the mix. The specific gravity of the solid particles is 2.61. Their liquid and plastic limits are 29.1% and 21.0%, respectively, with a plasticity index of 8.1.

Compaction properties

The maximum dry density and optimum water content of CGS mixtures, with different fines content (i.e., 5%, 7%, 9%, 11%, 15%, 20%, and 30%), were obtained by surface vibrating compaction test and the results are listed in Table 2.

The optimum water content of CGS increased gradually with the fines content (Table 2). The maximum dry density, however, first increased and then decreased with fines content increments, and the corresponding fines content of peak point is 9% (Table 2). These findings indicate that the maximum fines content is 9%, at which the required compaction effect of CGS could easily be met.

Testing program and sample preparation

The testing program was designed to investigate the effects of fines content, dry density, overburden pressure, and water supply on the frost susceptibility of the soil. A total of 47 samples were prepared varying these. Table 3