

Effects of particle size distribution and moisture content on the frost heaving behavior of unsaturated subbase material

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ABSTRACT: Subbase materials judged to be non-frost-susceptible based on frost-heaving tests have often experienced frost heaving, resulting in pavement damage. Owing to the high airtightness of the asphalt layer, the ground beneath the pavement allows limited escape of water vapor and tends to become a high-humidity environment. When a temperature gradient exists under such high-humidity conditions, water vapor moves from high temperature areas to low temperature areas, leading to condensation and freezing, eventually causing frost heaving even in coarse-grained soils. However, the mechanisms underlying frost heaving in unsaturated coarse-grained soils, induced by water vapor movement, condensation, and freezing, remain poorly understood. Therefore, the objective of this study is to clarify the effects of particle size distribution and initial water content on the frost heaving behavior of coarse-grained soil, such as a subbase material. Frost heaving tests were conducted under 100% relative humidity using a newly developed test apparatus for investigating unsaturated frost heaving. The results of unsaturated frost heaving tests demonstrated that frost heaving occurred even in unsaturated subbase materials when the tests were conducted in a high-humidity environment, with ice layers growing within the specimen. The amount of frost heaving tended to increase as the mean particle diameter decreased, with both the rate of frost heaving and amount of frost heaving increasing as the particle fineness increased. This indicates that susceptibility to unsaturated frost heaving is strongly dependent on the particle size distribution. Furthermore, the amount of frost heaving tends to increase with increasing initial water content. In addition to the water vapor absorbed from outside the specimen, the pore water within the specimen also contributed to frost heaving.

KEYWORDS: Coarse-grained soil, unsaturated soil, frost heave.

1 INTRODUCTION

Damage to civil engineering structures caused by frost heave and freeze–thaw action continues to occur frequently in Hokkaido, a cold and snowy region. Specifically, damage to roads that extend over long distances is particularly pronounced. Generally, frost heave occurs in fine-grained soils under freezing conditions, when there is a supply of moisture and a moderate temperature gradient. Therefore, soil type, moisture, and temperature are commonly referred to as the "three elements" of frost heave. Countermeasures typically aim to eliminate one of these elements. In Japan, the most common frost heave countermeasure for roads involves the replacement method in which frost-susceptible soil is replaced with non-frost-susceptible materials at the expected freezing depth. However, road surface uplift, which is suspected to be caused by frost heave, has been observed even when the freezing front reaches only the subbase or frost-protection layer composed of non-frost-susceptible materials. Moreover, frost heave tends to occur despite the soil having been replaced with non-frost-susceptible materials at the theoretical maximum freezing depth. For example, in a municipality in Hokkaido, frost heave was observed at a site where the soil had been replaced with non-frost-susceptible materials at the theoretical maximum freezing depth, as shown in Figure 1. At this location, there is no groundwater table within the replaced depth, and even the capillary rise of the subbase material is unlikely to transport sufficient moisture to the freezing front. Thus, although two of the three elements required for frost heave were missing, a surface displacement of approximately 7 cm was recorded. Similar occurrences of frost heave in subbase materials have been reported, prompting recent research on frost heave in unsaturated coarse-grained soils. According to these studies, asphalt layers are vapor-impermeable, which often leads to high-humidity conditions in the underlying soil owing to the lack of vapor escape pathways (Yao et al. 2016). Under such high humidity and temperature gradients, water vapor tends to migrate from the warmer side to the cooler side, resulting in condensation and freezing. Consequently, frost heave can occur even in coarse-grained soils (Teng et al. 2022).

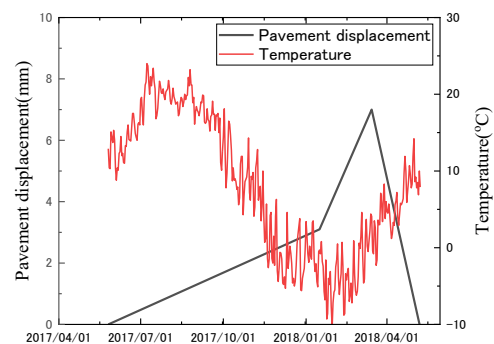


Figure 1. Pavement displacement at the section with countermeasures.

However, research on frost heave caused by vapor migration in coarse-grained soils, which are traditionally regarded as non-frost-susceptible materials, is still in its early stages, and the underlying mechanism is not yet fully understood. Therefore, in this study, we conducted frost heave tests under unsaturated conditions using a newly developed test apparatus. These tests investigated the effects of gradation and initial water content on the frost heave susceptibility of subbase materials previously classified as non-frost susceptible by conventional frost heave tests.

2 FROST HEAVE PHENOMENON ADDRESSED IN THIS STUDY

Frost heave is a phenomenon in which ice lenses form and grow during the freezing of fine-grained soil, causing the soil to expand under appropriate temperature and moisture conditions. In general, subbase materials composed of coarse-grained soils contain a low percentage of fine particles and are therefore classified as non-frost-susceptible materials. Consequently, frost heave in pavement structures has long been considered to typically occur when the freezing front penetrates the subbase

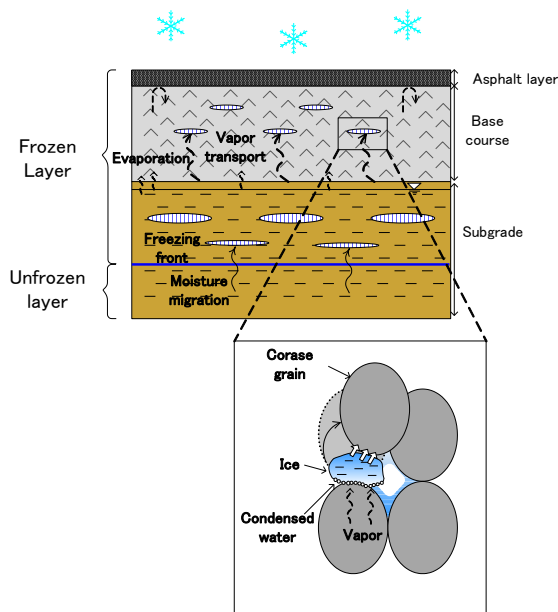


Figure 2. Frost heave of the unsaturated subbase material.

and reaches the subgrade, leading to pavement cracking. However, recent findings have revealed that frost heave can also occur in coarse-grained materials such as subbase soils. The phenomenon targeted in this study is illustrated in Figure 2. In coarse-grained soils, vapor migration is considered to be the water source for frost heave. The subbase and subgrade layers are sealed under highly impermeable asphalt surfaces and tend to develop high-humidity conditions because of the limited escape of water vapor. In cold regions during winter, surface cooling induces a temperature gradient within the ground, prompting water vapor to migrate from the warmer to the cooler side. This vapor condenses on the particle surfaces, resulting in increased moisture content. When the temperature falls below 0°C, the condensed water freezes, and the growth of ice crystals pushes up the soil particles. Consequently, frost heave is believed to occur even in coarse-grained subbase materials. Frost heave is traditionally defined as a process in which the pore water pressure at the ice lens interface decreases, which causes water from the unfrozen zone to be drawn into the freezing front, where it subsequently freezes and contributes to ice lens growth. In this study, ice formation and growth were also observed in coarse-grained soils. Since this phenomenon cannot be explained solely by the 9% volumetric expansion associated with the phase change of water to ice, the frost-induced expansion observed in coarse-grained soils is referred to as "frost heave" in this research.

3 MATERIALS

The test specimens used in this study consisted of crushed gravel, which was used as a replacement material in a municipality in Hokkaido. The grain size distribution of the material was adjusted according to the grading specifications of Crusher-Run C-20, as defined by the Japanese Industrial Standards (JIS), which specify a maximum particle size of 20 mm, considering the dimensions of the testing mold. The particle size distributions of the specimens are shown in Figure 3. Three types of grading conditions were adopted: the upper and lower limits specified in the grading requirements, as well as a distribution with finer particles than the upper limit. The test material was separately evaluated using the test method for

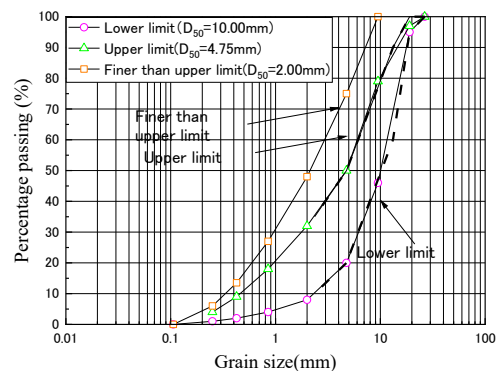


Figure 3. Grain size distribution.

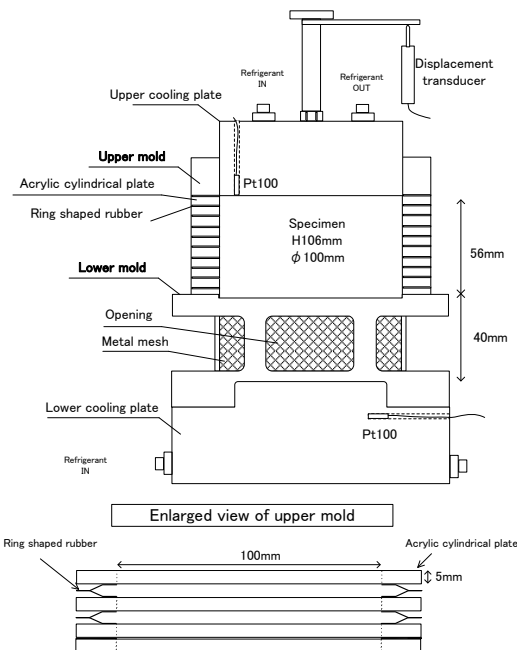


Figure 4. Test apparatus.

determining the frost susceptibility of soils (JGS 0172), and the material was confirmed to be a non-frost-susceptible material.

4 TESTING APPARATUS AND PROCEDURE

In this study, a frost heave test was conducted using a two-layer mold apparatus, as illustrated in Figure 4. The condensation and freezing of water vapor under high-humidity conditions, caused by an asphalt pavement covering the ground surface and subsequent cooling from the surface, were simulated. The upper mold section consisted of ten 5 mm-thick acrylic cylinders stacked vertically, with each cylinder bonded using ring-shaped rubber gaskets. This flexible structure was designed to reduce the effect of frost adhesion during freezing from the top.

The lower mold section included openings to allow humidity control during testing. A wire mesh with a 42 μm opening was installed over the aperture, which prevented soil loss while enabling moisture supply. The upper and lower cooling plates were connected to a refrigerated water bath, which allowed the coolant to circulate and maintained the specimen at the target temperatures. This configuration permitted the imposition of arbitrary thermal gradients to freeze the specimen. The test apparatus was installed in a polyvinyl chloride (PVC) box located within a cold room facility, enabling constant ambient temperature and humidity during

Table 1. Test condition.

No.	Purpose	Grainsize distribution	Dry density	Initial water content	Top water supply	Gravitational drainage
1	Particle size distribution effect	Lower limit	1.8 g/cm ³	10 %	✓	✓
2		Upper limit	1.8 g/cm ³	10 %	✓	✓
3		Finer than upper limit	1.8 g/cm ³	10 %	✓	✓
4	Initial water content effect	Upper limit	1.8 g/cm ³	5 %	-	-
5		Upper limit	1.8 g/cm ³	8 %	-	-
6		Upper limit	1.8 g/cm ³	10 %	-	-

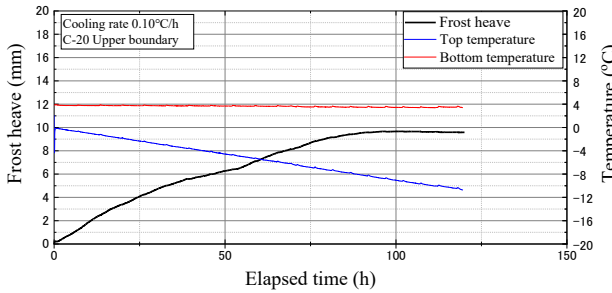


Figure 5. Time variations of frost heave and temperature (No.2).

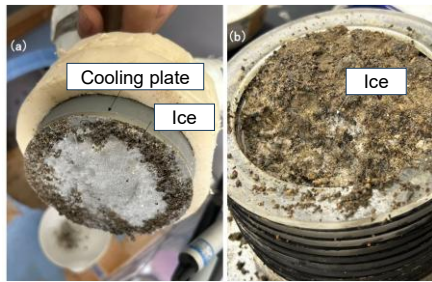


Figure 6. Ice layer (a) at cooling plate-specimen interface (b) in soil.

testing. To evaluate the effects of the particle size distribution and initial water content on frost susceptibility, tests were conducted under the conditions summarized in Table 1. The specimens were prepared by adjusting the moisture content of the test material to a predetermined level, placing it in a test cell, and compacting it to a dry density of 1.8 g/cm³. To evaluate the effect of the particle size distribution, 500 mL of water was poured onto the top of the specimen after preparation, followed by 2 h of gravitational drainage at room temperature. The test cells were placed in a PVC box and adjusted to 100% relative humidity. The top and bottom temperatures of the specimen were maintained at 0°C and 4°C, respectively, for 24 hours to allow further drainage, resulting in a total of 26 h before the start of freezing. To evaluate the influence of the initial water content, the test device was placed in a humidity-controlled box immediately after specimen preparation and freezing was initiated without supplying water to the top of the specimen. While maintaining the bottom temperature at 4°C, a thermal shock was applied, initiating freezing from the top of the specimen at a constant cooling rate. No additional load was applied to the upper cooling plate, except for its own weight. The cooling rate was set at 0.10°C/h for all tests.

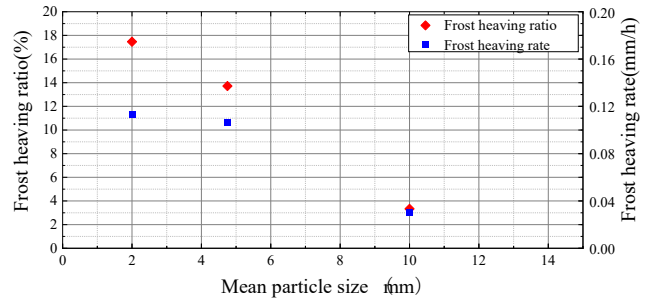


Figure 7. Frost heave ratio and frost heave rate versus mean particle size.

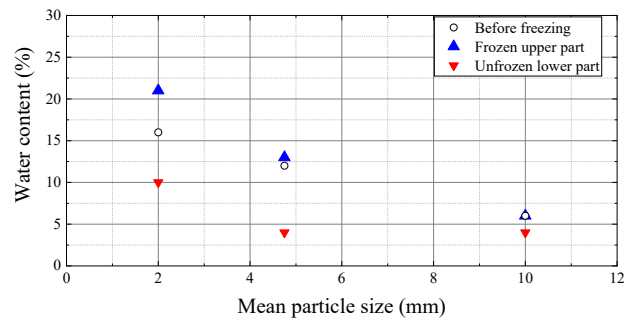


Figure 8. Pre- and post-test water content.

5 RESULTS

5.1 Effect of Particle Size Distribution on Frost Susceptibility

Figure 5 presents a representative example of the temporal variation in frost heave for the C-20 upper-limit gradation (Test Condition 2). Although frost heave mechanism in unsaturated coarse-grained soils differs from that in fine-grained soils involving ice lens formation, the term "frost heave" is used here to describe volumetric expansion due to freezing. As shown in Figure 5, despite being classified as a non-frost-susceptible material, the specimen exhibited frost heave of approximately 10 mm as the temperature decreased. This result is noteworthy, considering that the material used in this study was previously classified as non-frost-susceptible based on the JGS0172 frost heave test, in which no heave was observed.

To investigate the location within the specimen where frost heave occurred, the specimen was disassembled in its frozen state after the test to observe the ice lens formation. Figure 6(a) shows an ice layer formed at the interface between the upper cooling plate and the specimen. When freezing is initiated from the top, as in this study, the upper cooling plate impedes vapor movement, resulting in ice accumulation at the boundary interface, which is consistent with previous findings (Bai et al.

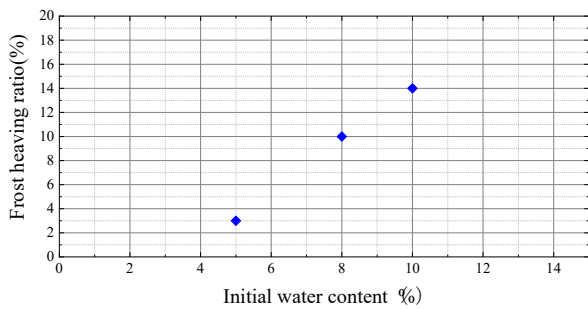


Figure 9. Relationship between initial water content and frost heave ratio.

2018). Furthermore, as shown in Figure 6(b), frost crystals were also found within the soil matrix, indicating that ice formation and the associated heave occurred not only at the boundary but also within the soil body.

Next, the influence of particle size distribution on frost susceptibility was examined. Figure 7 illustrates the relationship among the mean particle size, frost heave rate, and frost expansion ratio. The results revealed a clear trend in which smaller mean particle sizes were associated with higher frost heave rates and expansion ratios. This can be attributed to the fact that fine-grained soils possess a greater water retention capacity, leading to a higher initial moisture condition at the start of the test, which may influence the frost susceptibility.

To further explore this hypothesis, the initial and post-test water contents of both the frozen and unfrozen sections of the specimens were measured, as shown in Figure 8. The data indicate that soils with smaller mean particle sizes have a higher initial water content. Post-test results showed that the frozen upper sections had a higher water content than the lower unfrozen sections, regardless of the direction of gravity. Given that the experiment was conducted under 100% relative humidity, the evaporation from the specimen into the external environment was considered negligible. Thus, it is unlikely that the lower part of the specimen dried because of evaporation.

Instead, the elevated water content in the upper frozen region suggests that water vapor evaporated from the higher-vapor-pressure region in the unfrozen zone and migrated toward the upper cooling surface, where it condensed and froze. This implies that soils with finer gradation, which retained more water at the beginning of the test, exhibited greater frost susceptibility owing to enhanced vapor-driven moisture migration and ice accumulation.

These findings indicate that the water retention capacity is governed by particle size distribution and significantly influences the frost susceptibility of unsaturated soils.

5.2 Effect of Initial water content on Frost Susceptibility

Figure 9 shows the relationship between the initial water content and the frost heave ratio. The frost heave ratio increases as the initial water content increases. This is likely because a higher initial water content ensures the availability of water required for ice lens growth, resulting in a greater frost heave strain.

Figure 10 shows the relationship between the initial water content and post-test water content in the frozen and unfrozen parts of the specimen. Regarding the post-test water content, regardless of the initial water content, the upper frozen part of the specimen had a higher water content than the lower unfrozen part. Even under low initial water content conditions, the water content in the upper part was higher, suggesting that the water from the lower part of the specimen moved upward

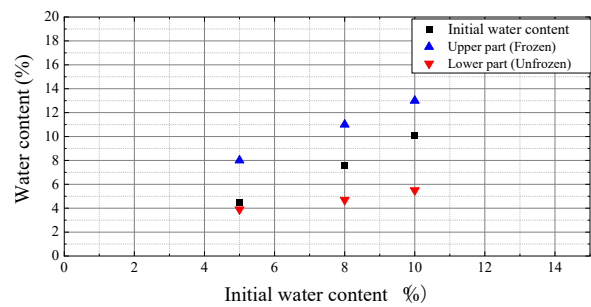


Figure 10. Pre- and post-test water content.

owing to the difference in saturation vapor pressure and subsequently condensed and froze. These results indicate that, in addition to the condensation and freezing of vapor from the air outside the specimen, the pore water within the soil also contributed to frost heave. The combined effects of capillary flow and the evaporation–condensation–freezing of water appeared to have led to ice lens growth and frost heave. Clarifying the mechanism of water migration to the upper part of the specimen remains a topic for future research.

6 CONCLUSIONS

In this study, a newly developed frost heave testing apparatus for unsaturated conditions was used to investigate factors influencing the frost susceptibility of unsaturated coarse-grained materials. Unsaturated frost heave tests were conducted under varying particle size distributions and initial water contents, yielding the following conclusions:

- Even unsaturated coarse-grained materials exhibited frost heave when tested under high-humidity conditions, as ice lenses formed within the specimen.
- The amount and rate of frost heave increased as the mean particle size decreased, indicating that the frost susceptibility under unsaturated conditions was strongly influenced by the particle size distribution. This is likely due to the differences in the water retention capacity associated with particle size composition.
- Frost heave increased with increasing initial water content. In addition to the water vapor migration from outside the specimen, the internal pore water also contributed to frost heave.

7 ACKNOWLEDGEMENTS

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