学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称　博士（工学）　氏名　WU Yuwei

学 位 論 文 題 名

Effect verification of wicking fabric on inhibition to frost heave at cold region pavement
(寒冷地舗装の凍上抑制に対するウィッキングファブリックの効果検証)

Pavements in the cold region may be seriously damaged by frost heave. The frost heave generates as follows: water in the large void freezes under the freezing point and results in ice crystals, meanwhile, the remaining water in small capillaries or absorbed as a film on the soil particle surface remain unfrozen. This unfrozen water has lower free energy at a lower negative temperature. Thus, the gradient of the water potential develops along with the gradient of the temperature. Thus, water may be drawn up from the warm portion and contribute to the formation of pore ice. Eventually, as the pores ice particles grow, they can connect with each other to form an ice lens, and this will result in the soil expanding. The expansion of soil in pavements during the freezing process may cause a significant deformation and result in road failures. To eliminate or reduce the freezing effect and inhibit the frost heave, reducing the moisture migration to the freezing front is an effective way. In order to inhibit frost heave during the freezing process, a new geotextile, wicking fabric (WF) that can drain water from the unsaturated frost- susceptible soil has been invented. However, the effectiveness of the WF in inhibiting frost heave during the freezing process was rarely invested in the previous studies. Therefore, in this study, both laboratory experiments and numerical simulations are conducted to investigate the inhibitory effect of WF on frost heave. As the soil in most of the base layers is unsaturated, experimental and numerical studies for unsaturated soil with and without WF installed were carried out to analyze the water migration during the freezing process. In the laboratory experiments, the one-dimensional frost heave tests were implemented to examine the frost susceptibility of soil samples, and the effects of various experimental factors (such as cooling rate, soil type, overburden pressure, water supply system, and initial saturation) on the frost heave. In addition, model tests were conducted to determine the frost heave inhibition effect by installing WF during the freezing process.

To better understand the inhibition effect of WF on frost heave, a thermo-hydro-mechanical (THM) coupled model was established. The proposed THM coupled model considers the interaction between the temperature field, the hydraulic field, and the mechanical field during the freezing process. The coupled relations are described by combining the Richards equation, the mass conservation equation, and the Navier equation. These partial differential equations are numerically solved by finite element software (COMSOL). The energy conversation equation is used to describe heat transfer and latent heat during ice-water phase change in the thermal field. The VG model is introduced to describe volumetric water content variation in unsaturated soils in the hydraulic field. The deformation of soil during freezing is described by introducing a linear elastic model in the mechanical field. Besides, in order to accurately simulate the water migration and the frost heave of soil-WF system during freezing, an evaporation model was developed to describe the boundary condition of the WF and reproduce the evaporation and water absorption process of the WF. The proposed evaporation model simplifies the water absorption and drainage process of the WF, taking into account the effects of ambient temperature, soil temperature, and soil water content variation during freezing on the water drainage efficiency of the WF. The model can quickly predict the drainage effect of WF during freezing,

while optimizing the simulation process of WF-soil system in which the water absorption effect of WF varies with the environmental conditions.

The validity and applicability of the THM coupled model are verified by comparing frost heave test results with the simulation results under different experimental conditions. Meanwhile, the validity of the evaporation model is confirmed by comparing the model test results with the simulation results. Both results show the effectiveness of WF on frost heave inhibition. Finally, the effect of different experimental conditions on the ability of WF to inhibit frost heave was investigated by simulating the model with and without WF under various experimental conditions (soil type, groundwater table, and cooling rate). According to the frost heave test, the frost heave is proportional to initial saturation and inversely proportional to cooling rate and overburden pressure. Furthermore, the opened system (with water supply) can cause a larger frost heave deformation than the closed system (without water supply). On the other hand, based on the model test results, soil samples with WF installed produce significantly less frost heave under the same freezing conditions than without WF. Moreover, soil types, cooling rates, and the groundwater table can also affect the efficacy of WF in inhibiting frost heave. WF produces better suppression in the following situations: soil samples with low permeability, low cooling rates, and a lower groundwater table.

Last but not least, since the existing models which use some ideal simplification conditions in predicting the inhibition effect of WF on frost heave may overestimate the suppression effect when the practical application may not meet the simplification criteria, the proposed model is applied to pavement sections with and without buried WF to illustrate the performance and practicality. By providing a continuous water supply and a sufficient contact surface between the WF and the surrounding dry atmosphere during the freezing process, the proposed model can successfully simulate the frost heave inhibition effect of the WF. The comparison of simulation results with experimental results has demonstrated the applicability of the proposed model in reproducing water migration in the WF-soil system. The model is also shown to be capable of simulating the effect of WF on frost heave inhibition accurately.

Chapter 1 introduces the background, objective, main technical path, and organization of this study. Chapter 2 introduces the development, classification, and summary of THM coupled models, and also summarizes the current state of research on WF. Chapter 3 introduces the theoretical foundations used in this study, including the THM coupling model and the evaporation model. Chapter 4 introduces the frost heave test with a THM coupled model built based on the theory proposed in Chapter 3 to verify the validity of the numerical model by comparing the test and simulation results. Chapter 5 presents the model tests of WF. By comparing the model test results with simulation results, the validity of the evaporation model is verified. Furthermore, the frost heave and water redistribution of both with and without the WF model are simulated under different experimental conditions. Chapter 6 shows the field test of WF in the test pavement and the numerical simulation to verify the performance and practicality of the numerical model proposed in this study. Chapter 7 summarizes the conclusions and recommendations of the study.