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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　SI Junling

学 位 論 文 題 名

Mechanical response and damage analysis of asphalt pavement subjected to wheel loads in seasonally cold region
(輪荷重を受ける積雪寒冷地のアスファルト舗装の構造解析手法の提案)

Asphalt pavement is a commonly used form of infrastructure exposed to various environmental impacts and traffic load actions. There has been increasing concern about the deepening of asphalt pavement damage. During the initial stage of service, most of the damage is usually on the pavement surface. However, damage can occur in the base and subgrade layers where the pavement has aged severely. Therefore, accurately predicting the fatigue life of asphalt pavement requires a comprehensive understanding of its mechanical response to significant environmental impacts. This becomes especially crucial in cold regions where temperature variations, moisture fluctuations, and freeze–thaw action can significantly impact the performance and durability of asphalt pavements.
Current Japanese theoretical pavement structure design method (TPSDM) uses mechanical empirical criteria to predict the fatigue loading number against fatigue cracking and rutting. Although the TPSDM is widely used for designing asphalt pavements in Japan, it still exhibits certain limitations, such as not considering the variation in moduli of the base and subgrade layers due to water contents, freeze–thaw action, and stress states. This study aims to enhance Japanese TPSDM’s accuracy by considering variations in the resilient modulus of environmental impacts, pavement materials, pavement structure, and traffic load actions to accurately calculate the mechanical responses and predict pavement fatigue life.
Firstly, the study develops a 3D Thermo-Hydro-Mechanical (THM) model using the finite element method (FEM). Based on a nonlinear elastic model and convergence analysis, the mechanical field is developed within the proposed coupled model. The thermal and hydraulic fields are established by the PDEs (partial differential equations). Secondly, this study uses ODEs (ordinary differential equations) to characterize the physical state of geomaterials and quantify the number of days passed during the recovery period on the element scale. Furthermore, modeling the geomaterials with a stress-dependent modulus is a typical coupling problem that involves a circular dependence among resilient modulus, matric suction, temperature, stress, and deformation. This circular dependence can be solved in the WF-PDEs (weak form partial differential equations) to define the stress-dependent modulus. Lastly, in a multi-layer elastic model, the structural response results can be generated by utilizing the resilient modulus, which is influenced by the stress state and environmental impacts. Based on empirical models, the structural response results can then estimate the expected allowable loading number against rutting and fatigue cracking. The method of modifying the rutting failure criterion by incorporating the MEPDG model and the PSAR effect enhances the practicality of the rutting model. To validate the proposed method, this study conducts a comparative analysis to compare its predictions with those

obtained using established pavement design methods. Additionally, field validation is conducted to confirm the effectiveness of the method in real-world scenarios by monitoring pavement moisture content and temperature changes, as well as actual fatigue life and modulus. Results indicate that the modifications improve the Japanese TPSDM by considering the environmental impacts, traffic load actions, pavement materials, and pavement structure, thereby improving the accuracy of predicting the fatigue life of asphalt pavements, particularly in cold regions.

The thesis is composed of 7 chapters. Chapter 1 introduces the study's background, objectives, and the need for improvement in the Japanese theoretical pavement structure design method. Chapter 2 provides an overview of several resilient modulus and permanent deformation prediction models for pavement materials, the THM coupled model and effect of principal stress axis rotation. Chapter 3 summarizes the environmental impacts on pavement systems and verifies the validity of the TH coupled model by comparing the measured and simulated results. Chapter 4 investigates the infiltration behavior of asphalt pavements under rainfall, with a specific focus on the hydraulic properties of the As layer and compares the applicability of single-phase and two-phase flow models in simulating such behavior. Chapter 5 establishes a system for evaluating the environmental impact on resilient modulus of pavement materials and verifies it through field measurements. Chapter 6 replaces the constant elastic modulus of the base layer and subgrade layer with an elastic modulus related to the stress state and complex environmental impacts, and modifies the rutting failure criterion, then examines the applicability of the modified design approach. Finally, Chapter 7 summarizes the study's findings, provides recommendations for pavement design improvements, and discusses enhancing pavement fatigue life.