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Degradation reliability modeling of stabilized base course materials based on a modulus decrement process

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HIGHLIGHTS

- A general framework of degradation-based reliability was developed.
- A degradation model to describe the evolution of degradation index was established and validated.
- A new approach to calculate reliability was established using Monte Carlo simulation.
- The developed approach can capture a real-degradation behavior of stabilized base course materials.

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ABSTRACT

The dynamic elastic modulus of stabilized base course materials is crucial to the design and evaluation of pavement, which has a great effect on the life-cycle performance of pavement. In this study, the fatigue performance of commonly used stabilized base course materials was investigated. A general framework of degradation-based reliability was developed. To accurately characterize the degradation process of dynamic elastic modulus, a degradation index was proposed and its failure threshold values were defined. A degradation model to describe the evolution of degradation index was established and validated. A new approach to calculate reliability was established using Monte Carlo simulation. The corresponding degradation-based reliability was conducted on the fatigue test data. Results show that the value of critical degradation index is significantly influenced by the properties. The proposed degradation model is capable of predicting the degradation index with high degree of accuracy. The developed degradation-based reliability approach is able to capture the more real-degradation behavior of stabilized base course materials. The degradation-based reliability includes three phases, which correspond to different degree of cracking. The mean value of fatigue life corresponds to reliability decreasing phase.

1. Introduction

With the economic growth and social development, there is an urgent need for reliable and durable transportation infrastructure in the modern society. Pavement, as one important component of transportation infrastructure, is closely related to people's life. Thus, people pay more and more attention to the design, rehabilitation, and maintenance of pavement, especially maintenance. In general, when asphalt pavement reaches the design life, the life of its surface and base is not the same, and the life of base is often greater than that of surface layer [1]. Therefore, the service condition of base layer should be evaluated to maintain the surface layer of pavement in a sound and rational manner.

Stabilized base course material, as one of the commonly used materials for pavement base, has been used satisfactorily and economically for the construction and rehabilitation of roads for the past few decades. Cement stabilized bases (CSBs), moreover, have been commonly used in areas subjected to heavy loads and in areas that lack quality aggregate sources [2]. The major distress modes involving the material are fatigue cracking, permanent deformation and thermal cracking, which have a significant influence on the services condition of stabilized base course [3]. The base deterioration generally can propagate to a pavement surface, leading to surface deterioration. For example, fatigue cracking, one of the major distress modes in pavements with stabilized base, is resulted from stabilized bases' modulus degradation under repeated loading. Cracks from fatigue failure generally originate at the bottom of a stabilized base layer and then propagate to an asphalt pavement surface. Therefore, it is still necessary to effectively make

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the prediction and evaluation of the health state of stabilized base course material, providing some guidelines for future design and maintenance of pavements.

In a practical project, stabilized base courses are usually subjected to repeated moving loading inducing flexural stresses, leading to some degree of irreversible accumulated damage. Considering that dynamic modulus is closer to the actual stress condition of a pavement [4,5], the cumulative damage can be characterized by the degradation of dynamic elastic modulus [6]. In addition, an information on the damage accumulated before the pavement materials up to failure point is important, which may be crucial in formulating a maintenance strategy. The dynamic elastic modulus characterizing cumulative damage is one of important parameters in the pavement design and mechanical analysis, its evolution is mainly a degradation process caused by the development of fatigue cracking and has a great effect on service life and mechanical responses in pavement layers [7,8]. For most pavements with stabilized base, however, the evolution of dynamic elastic modulus for stabilized base course materials hasn't been considered in the pavement design and evaluation in some countries [9,10], and so it is necessary to explore the dynamic elastic modulus degradation of these materials.

Numerous successful applications of stabilized base course materials were also widely reported in the literatures [11–18]. The dynamic modulus is a critical material property in the characterization of these materials, exhibiting significantly performance degradation characteristic under repeated loading [6,14,19–25]. Some studies indicated that the dynamic modulus degradation pattern of these materials, including cement stabilized macadam (CSM), cement stabilized gravel (CSG), lime-fly ash stabilized macadam (LFASM), cement stabilized fine grained soil (CSFGS), and cement stabilized recycled aggregate, had three stages: rapid decline stage, steady decline stage and sharp decline stage [20,26–28]. These materials are becoming more and more common and hence of practical importance. Degradation of dynamic modulus reflects a weakening process of mechanical properties of material, and considering the above degradation characteristic, the selection of effective modulus value in pavement design must be combined with the three-stage degradation [29,30]. There are many work on the three-stage degradation in detail. Jia calculated the change rate of modulus for the second stage [31]. Furthermore, Sobhan et al. evaluated the elastic properties of the stabilized base course material with recycled aggregate and found that the dynamic elastic modulus of most samples decreased slowly with the increase of loading cycles and the degradation at or near failure did not exceed 25% of the initial modulus [6]. Thøgersen et al. regressed and predicted the resilient modulus of asphalt pavements with stabilized base and found that the modulus degraded to 30% of the initial modulus after 10^6 cycles [32]. To summarize, although the degradation of dynamic elastic modulus exhibits significant three stages under repeated loading in all above literatures, the degradation process is only qualitatively described without quantitative analyzation. Subsequently, according to the degradation rule of dynamic modulus, the relationship between the dynamic modulus and fatigue damage was given [33]. An incremental recursive damage model of CSB materials has been established, and dynamic elastic modulus parameters were introduced to indicate the extent of damage [34,35].

The previous studies show that the degradation process of dynamic modulus for stabilized base course materials includes three stages, and several models characterizing the process have been established. But these models fail to reflect the degradation characteristics of dynamic elastic modulus under repeated loading accurately. In addition, the existing models focus on the deterministic degradation process, however, the degradation of dynamic elastic modulus under repeated loading is stochastic in nature. The stochasticity is caused by the inherent variability in performance of materials as well as the uncertain nature of loads experienced by the materials. There is considerable interest in developing a new general simulation technique to predict the performance degradation of materials through probabilistic modeling. From both deterministic and probabilistic points of view, a conventional method fails to make an assessment of variability and uncertainty as well as an estimation of the probability degradation process accurately. For the calculational complexity, a simple approach is developed to characterize the uncertain nature of degradation modeling of stabilized base course materials in this study. This approach is capable of minimizing the computational complexity and can be explained by well-known physical laws. Moreover, it can be effectively used for degradation reliability analysis of these materials under repeated loading. For pavement reliability, it also provides a new idea for evaluating the reliability of existing pavements.

To make full use of degradation information and effectively assess the health status of these materials, the objectives of the study are to develop a general framework of degradation-based reliability; propose a performance degradation index and determine its failure threshold; establish and validate the degradation model describing the trend of degradation index; establish a new approach to calculate degradation-based reliability using Monte Carlo simulation procedure; and evaluate degradation-based reliability of stabilized base course material based on the proposed method.

2. Degradation-based reliability

To date, the reliability of asphalt pavement still faces a number of old problems and new challenges. Existing pavement reliability studies [36–39] focus on distress models in pavements, leading to the difficulty of calculating system reliability and maintaining pavements. Asphalt pavement is usually subjected to a coupling effect of environment and load for a long time, resulting that its bearing capacity and service performance degrade with the increase of service time [40]. If the performance degradation is not considered, it would be meaningless to only analyze and evaluate the reliability in the target period.

There has an effect of all kinds of uncertain factors on performance of pavement materials [41]. There has also many uncertain factors in the degradation process of dynamic modulus of materials in this study. Thus, the degradation of dynamic modulus in this study is an uncertain process which is not described by a conventional certainty method. It is necessary to model the degradation process of dynamic modulus based on the reliability theory, because the theory is a decision method to deal with the problems of uncertainty in engineering.

Based on the above-mentioned analysis and the definition of performance failure, the reliability analysis should be conducted to more reasonably assess the quality of stabilized based course materials, improving the service life of asphalt pavement [41]. For the traditional reliability theory or failure-based reliability, however, sudden failure mechanism is used to analyze the health state of materials or structures, so the state evolution of materials or structures isn't considered in the failure process, resulting that the reliability theory is incapable of solving future the specific problems in practical engineering. Considering the degradation properties of pavement materials and the problems exited in traditional reliability theory, the degradation-based reliability is proposed to make full use of information in a failure process. The framework of degradation-based reliability is shown in Fig. 1. The degradation-based reliability of materials or structures is conducted by following ways: