Construction and Building Materials 68 (2014) 572–579

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Reliability-based assessment of deteriorating performance to asphalt pavement under freeze–thaw cycles in cold regions

Wei Si [1], Biao Ma *, Ning Li, Jun-ping Ren [2], Hai-nian Wang [3]

Key Laboratory for Special Area Highway Engineering of Ministry of Education, Chang'an University, Xi'an, Shaanxi 710064, China

HIGHLIGHTS

- Compressive characteristics have been analyzed under freeze–thaw cycles.
- Reliability method was applied to analyze the pavement reliability functions with various uncertainties.
- Pavement capacity under freeze–thaw cycles was studied based on reliability method.

ARTICLE INFO

Article history:
Received 25 October 2013
Received in revised form 8 June 2014
Accepted 3 July 2014

Keywords:
Freeze–thaw cycles test
Resilient modulus
Reliability method
Monte Carlo Simulation
Fragility curves

ABSTRACT

Accurate deterioration models play a critical role in designing and managing transportation infrastructure. Regular models just consider loading factor and its relative uncertainties. However, climate and environment impacts are not considered or just taken as certain variables. Thermal cracks and moisture distresses are principal distress forms in cold regions, where early damage is more significant than general regions. In this paper, Freeze–Thaw (F–T) cycle test was performed to investigate the impact of the cold climate and moisture resistance on paving mixtures, and the compressive strength and resilient modulus were studied. Then reliability method was applied to analyze the pavement reliability functions with various uncertainties. The analytical results showed that the resilient modulus of asphalt concrete mixture declined under F–T cycles. Consequently, pavement structure capacity was reduced. The results also illustrated that reliability method was capable of accommodating uncertainties in pavement parameters. The sensitivity analysis addressed that F–T cycles had a significant impact on estimating reliability, especially with the large coefficient of variance. The larger coefficient of variance, the faster reliability declined. Reliability analysis results indicate that decrease in variability of F–T cycles can significantly increase the estimated reliability. As a result, F–T cycles with uncertainty do harm to pavement loading capacity, which should not be neglected in actual engineering. This paper also proposes some instructions on simulating pavement performance models.

1. Introduction

All civil infrastructures are faced with the problem of deterioration, and it has been recognized as a critical issue worldwide [1,2]. Pavement is a significant part of transportation infrastructure, which is exposed in atmospheric, and suffers the climatic, environmental effect, and vehicular load directly [3]. Asphalt is a thermoplastic material, and asphalt concrete (AC) mixtures present viscoelastic characteristics as well [3]. Numerous studies have found out that distresses of pavement have important relationship with climate and environment as well as loads [3,5]. Previous researches showed that temperature and moisture are the most impact factors to asphalt pavement performance [3–7]. Due to the sensitivity to temperature and moisture, asphalt pavement's performance and serviceability are prone to deteriorate than other infrastructures. Thermal cracks, moisture damage and other low temperature distresses are the key issue for asphalt pavement in cold regions [4].

Low-temperature cracking and thermal fatigue cracking are the two forms of thermal cracking in asphalt pavement [3]. When temperature falls rapidly or in continuous low temperature, temperature stress is formed in asphalt pavement. Low temperature

* Corresponding author. Tel.: +86 (029) 82334646.
E-mail addresses: siweichd@gmail.com, siwei26@utexas.edu (W. Si), mabiaochd@163.com (B. Ma), 630589426@qq.com (N. Li), jpren1990@163.com (J.-p. Ren), wanghainian@yahoo.com.cn (H.-n. Wang).
[1] Tel.: +86 150 9401 1268.
[2] Tel.: +86 151 9146 7341.
[3] Tel.: +86 136 0916 1519.

http://dx.doi.org/10.1016/j.conbuildmat.2014.07.004
0950-0618/

cracking occurs when the thermal tensile stress in asphalt pavement exceeds its tensile strength [3,4]. If the comprehensive stress (temperature stress, load stress, etc.) is smaller than the tensile strength, the interior micro-damage will accumulated rather than forming cracks. After a large number of Freeze–Thaw (F–T) cycles, the comprehensive stress exceeds the ultimate tensile strength of asphalt mixture, which leading to cracks and other apparent distresses [5,6]. Moreover, if the pavement is located in the moisture environment, hydrodynamic pressure and vacuum constriction will appear in the surface layer under repeatable vehicle loads [5–7]. Water causes the disruption of the bond between the asphalt and the aggregate at the asphalt-aggregate interface. This premature failure of adhesion is commonly referred to as stripping in asphalt concrete pavements [1]. F–T cycles will result in stripping aggravation and voids increase on the surface of AC. Several pavement distresses that can include stripping as the underlying cause are rutting, cracking, raveling, flushing, and bleeding, furthermore which accelerates the degradation of pavement load capacity.

During the F–T cycles test, the damage of asphalt mixtures is initiated by ice expansion load and accelerated by the interfacial damage between asphalt and aggregate or fracture of asphalt mortar. The change of volume should be caused by the expansion of water under low temperature in mixtures. The expansion will enlarge the gap voids of the internal composition and reduce the tensile strength of mixtures. Asphalt-aggregate bond is easily displaced from the aggregate by water under the impact of F–T cycles, which weakens the asphalt–aggregate bond and increases the stripping of aggregate.

Many researchers studied F–T of various materials by using a number of laboratory tests. Most of them were related to the determination of the effects of F–T on the properties of materials such as strength, compressibility, porosity, pore size distribution, and permeability. In most cases F–T cycling of the samples is limited to one cycle, or some fixed cycles, it has not presented the mixtures' deterioration trend with F–T cycles increasing. Lots of researchers tried to explore the mechanism of AC performance suffering temperature and moisture in cold regions. However, due to the differences in experiment, model, and simulation method, no standard evaluation criteria are built at yet.

In this paper, F–T cycle test is proposed to analyze the influence of temperature and moisture on AC. During the F–T cycles experiment, environment temperature changes from positive to negative repeatedly, and the samples suffer repetitive thermal tress and moisture impact. The deterioration of AC can be obtained through F–T cycle test. However, the test result just presents the deterioration trend of AC, which is not connected to the design equation or pavement performance. Also, previous research neglected to combine the materials' experimental properties with pavement design and performance evaluation. Consider with these drawbacks, reliability method is applied in this paper to analyze the asphalt pavement AASHTO design equation based on the variation of AC's compression properties under F–T cycles. Reliability is an important performance measure of pavement structural (performance) condition and reliability-based procedures have the capability of accommodating uncertainties in assessment.

More uncertainties will arise in pavement structure assessment when AC is under F–T cycles. Reliability models are probabilistic models, which predict the failure probability of a given system. The limit state function for flexible pavements is typically defined as a difference between the designed load applications. The supply of a pavement is a criterion that can withstand certain loads before failing, and the number of load applied is called demand correspondingly [8]. If there is a clear definition of a failure event and the consequence of the failure, reliability models can be effectively used to predict the performance and lifetime of pavements [1]. Reliability models distinguish only two conditions or states: a functional (surviving) state and a failure state. Under F–T cycles, it directly impacts the states of reliability model.

The objectives of this research are to analyze the degradation of resilient modulus of AC under F–T cycles, and to use reliability method to illustrate the impact of F–T on AC structure capacity behavior by the number of 18-Kip (80-KN) single axle load. The scope of the paper is limited to the consideration of variability associated with the response and utilization of pavements.

2. Experimental and reliability methods

2.1. Materials and F–T cycle test

2.1.1. Materials used

The materials used in laboratory study were: Asphalt, aggregates, and filler; which were used as virgin materials. Asphalt is SBR (Styrene Butadiene Rubber) modified asphalt; aggregates and filler were obtained from lime-stone. Test results of asphalt are presented in Table 1. Various engineering properties of asphalt, aggregates and filler have met specifications and standards through the experimental test.

AC used in this research with the 13 mm nominal maximum aggregate size AC-13 mixture, as recommended by the specification of Ministry of Transportation of China, which is listed in Table 2[9].

The optimum asphalt content (OAC) of the asphalt mixture was obtained by applying Marshall Test: the cylindrical specimens made by the standard compaction hammer and cylindrical mold were 101.6 mm in diameter and 63.5 mm in height [9]. On the basis of Marshall Test and considering the climate of cold regions as well as traffic conditions, the final OAC of AC-13 is 5.5% in this research.

2.1.2. Freeze–thaw cycle test

F–T cycle test first used in civil engineering is to evaluate the impact of F–T cycles on the performance of cement concrete [10,11] and soil [12,13]. As the application of flexural pavement increases in cold regions, some researchers noticed that asphalt pavement also suffered F–T cycles influence.

In terms of AC F–T cycle test, there is no standard due to the differences on climate conditions. In AASHTO T283 testing procedure, the conditioned specimens were vacuum saturated to 70–80% saturation. Each vacuum saturated specimen was tightly covered with plastic wrap and placed in a plastic bag with approximately 10 ± 0.5 mL of water, and sealed. The plastic bags were placed in a freezer at −18 ± 3 °C for 24 h. The specimens were removed from the freezer and placed in a water bath at 60 ± 1 °C for 24 h with 25 mm of water above the specimens. After 24 h in the 60 ± 1 °C water bath, the specimens were removed and placed in a water bath at 25 ± 0.5 °C for 2 h ± 10 min to achieve room temperature [14]. In one research, the samples were soaked in water for 12 h at room temperature, then each was covered with plastic wrap, sealed in a plastic bag, and placed in an environmental chamber for 12 h at −17.8 °C.The conditioned samples were exposed to seven 24 h cycles [15]. One of the typical researches in China was firstly water conditioned by vacuum saturation for 15 min, and then subjected to 8 successive cycles of freezing and thawing. Each cycle was consisted of freezing at −20 °C for 8 h followed by soaking in water at 60 °C for 4 h [5].

Considering present F–T cycle test, a modified F–T cycle test was proposed in this paper. In the F–T cycle test, specimen was placed in the plastic bag and 30 ml water was injected in the plastic bag, and sealed. Freeze temperature is −25 ± 1 °C and lasts12 h; then put the specimens into water-bath to be thawed at 25 ± 1 °C and lasts12 h as well. The freezer and water-bath are used to simulate the F–T cycles.

Table 1
Test results of asphalt parameters.

Asphalt state	Test item	Test temperature	Result
Original sample	Penetration/0.1 mm	15 °C	51
		25 °C	123.1
	Softening point (R&B) (°C)	–	47.6
	Ductility (cm)	5 °C	>150
	Density (g cm^{-3})	25 °C	1.023
	Flashing point (°C)	–	>260
	Solubility (%)	–	99.6
After aging	Mass Loss (%)	–	0.2
	Vestigital penetration ratio (%)	15 °C	65.3
		25 °C	58.1
	Ductility (cm)	5 °C	>150