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Laboratory investigation of rutting performance for multilayer pavement with fiber Bragg gratings

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HIGHLIGHTS

- Specific FBG sensors were designed to monitor the deformation in asphalt mixtures.
- The deformation of asphalt specimens were monitored at different temperatures in different depths.
- A revised linear viscoelastic rutting prediction model was adopted and its reliability was proved.

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ABSTRACT

Rutting is a significant problem for asphalt pavements, caused by factors such as channelized traffic and over loading, especially in urban areas and on highways. In recent decades, great emphasis has been put on this issue through various research methods. Fiber Bragg grating (FBG) sensing technology is widely used to detect the structure conditions due to its accuracy and simplicity and now gradually applied to pavements as a common detecting method. The objective of this study is to use FBG sensors to monitor the inner accumulated deformation of asphalt specimens in various depths at different temperatures, and seek for the relationship between accumulated deformation and temperature through an improved linear viscoelastic rutting prediction model. The results showed that the FBG sensors are reliable for monitoring accumulated deformation of asphalt pavements. For the full-depth rutting specimen, the deformation in the top and lower layer changed significantly with temperature. The middle layer had the largest unit accumulated deformation, which was not sensitive to temperature. It was also concluded that the revised model had enough accuracy to predict deformation of pavements, regardless of materials or structures.

1. Introduction

With the increasing traffic on flexible road, rutting has become one of the most significant problems for road pavements in recent decades, especially in urban areas due to the channelized traffic and overload [1]. Due to the sensitivity of asphalt pavements to temperature, it's easier to form ruts under the effect of loading and high temperatures. For this reason, some modified asphalt mixtures were chosen to improve its temperature sensitivity [2]. However, temperature is still the most significant factor to the asphalt behavior in the compaction stage or the rutting resistance in the service period for pavements [3–5]. Considerable amount of researchers have put emphasis on rutting performance analysis and making predictions on some road behaviors to ensure highway and urban roads a longer lifetime.

There have been many researches focusing on the pavement performances of asphalt mixtures. Bekheet et al. (2004) evaluated the in-situ shear properties of asphalt concrete mixes by using the newly developed in-situ shear stiffness testing facility, versus the laboratory evaluation by using the resilient modulus and torsion testing. The results showed that the in-situ shear stiffness had the highest correlation coefficient with rutting rate [6]. Wang et al. (2014) found that the use of recycled asphalt shingles (RAS) in open-graded friction course (OGFC) could enhance its rutting performance, and generally increased indirect tensile strengths [7]. Xue and Weaver (2015) studied the influence of tire configuration on pavement and provided some suggestions on it from the perspective of reducing pavement damage. The results indicated that wide-based tires with wider interface could be road-friendly [8].

Walubita et al. (2012) used Hamburg wheel tracking, dynamic modulus, and repeated load tests to evaluate the rutting resistance of hot-mixed asphalt (HMA) and related it to the field performance

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[9]. Yang et al. (2009) performed a case study of rutting prediction in two separate ways. The empirical method is capable of predicting rut depth within the whole design life, and theoretical method by integrating a four-element-five-parameter viscoelastic model and the layered strain approach was provided inadequate because of the limitation of the model itself and also of the method for obtaining parameters [10]. Zhao and Wang (2015) measured International Roughness Index (IRI) through dynamic tire pressure sensor inside the tire, which could reflect distresses such as severe cracking, potholes, and rutting, etc. The newly developed method has the potential to be integrated into vehicle computer systems to form a network wide global health monitoring system of roadways [11]. A wireless sensing network was designed to illustrate the great potential of the complete pavement health monitoring system by using common commercial off-the-shelf pavement sensors, which could monitor road distresses like fatigue and rutting [12]. Each test method above has its own advantages, for example the IRI method due to its innovation. However, these methods are confined in the laboratory test or just not suitable to the practical engineering.

In recent years, the structural health monitoring (SHM) system was increasingly applied to the structures in civil engineering, which allows constructors to have a better understanding of structure condition. Optical fibers are usually chosen as sensing elements due to its simplicity and accuracy [13]. However, this technology is still in the practice stage, especially on pavement monitoring.

Fiber optical grating sensors were used in monitoring road temperature on the I-84 freeway in Minnesota to investigate temperature contraction cracking of roads [14]. Tan et al. (2014) proved that the fiber Bragg grating (FBG) sensing technology could identify the weak compacting areas based on different FBG sensor response values and serve for long-term monitoring of pavement structural behavior [15]. Liu et al. (2011) made the co-line and integration design of FBG sensors and BOTDR (Brillouin Optical Time Domain Reflectometry) sensors, which could provide real time subgrade settlement and rutting information. Its potential and feasibility of the practical application were proved in the lab tests [16]. FBG sensors could also be applied and work well in the severe environments like high temperature or moisture condition [17,18].

Above all, it can be seen that these researches are mostly used to verify the feasibility of FBG sensing technology by testing its packaging craft, sensitizing effect, survival rate of embedded sensors and reliability in monitoring of pavement conditions. However, most of them use FBG sensors to measure the stress and strain of pavement structure under different loading conditions. The accumulated deformation of pavement is rarely monitored by FBG sensors, especially at different temperatures.

In this paper, asphalt pavements are mainly researched by using embedded FBG sensors to monitor the accumulated deformation of full-depth rutting asphalt specimen. The changes of accumulated deformation in pavements could be concluded after simulating the real loading conditions at various temperatures.

Table 1
Aggregate gradations of asphalt mixtures and mix design.

Mixture	SMA-13	AC-16	AC-25
Optimal Asphalt Content (%)	5.6(SBS)	4.7(70#)	4.1(70#)
VV (%)	4.0	4.6	4.3
VMA (%)	16.6	14.3	12.5
VFA (%)	76.0	68.0	65.2
Flow (10^{-1} mm)	35.6	35.5	29.5
Marshall Stability (KN)	10.19	14.62	11.87
Sieve Size (mm)	Passing Percent (%)		
31.5	100	100	100
26.5	100	100	99
19	100	100	84
16	100	89	74
13.2	95	70	65
9.5	63	42	54
4.75	27	31	35
2.36	21	25	24
1.18	19	20	17
0.6	16	15	12.5
0.3	14	11	9
0.15	13	7	7
0.075	12	5	5

2. Objectives

The main objective of this paper is to study and predict the change rule of accumulated deformation for asphalt mixture at different temperatures by using the fiber Bragg grating sensing technology and an improved rutting prediction model. The prediction results were compared with the measurement values to assess the reliability of improved model.

3. Materials and mix designs

The full-depth rutting specimen has three layers, named as the top layer, middle layer and lower layer, which represents the typical asphalt pavement structure. The SMA-13 mixture was selected for the top layer, which has been widely used as wearing course of asphalt pavements in China and the thickness was set to be 40 mm. The AC-16 and AC-25 mixture were chosen for the middle and lower layer and their thickness were 50 mm and 60 mm, respectively. The aggregate gradation and mix design parameters can be found in Table 1. Two asphalt binders used were styrene-butadienestyrene (SBS) modified asphalt (PG 76-22) for the top layer and 70# asphalt (PG 64-22) for the middle and lower layers. Four replicates were made for tests at four different temperatures.

4. Design and calibration of FBG

Polypropylene was considered to be the packaging material of FBG sensors according to the requirement of packaging. Epoxy

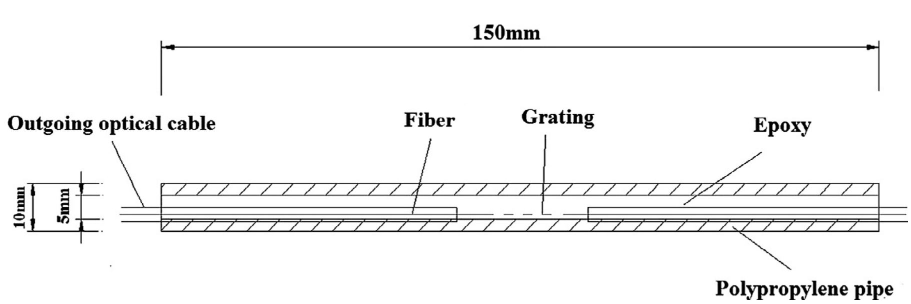

Fig. 1. Size of pipe for FBG sensors.