Generation and propagation of reflective cracking and thermal cracking of asphalt pavement in cold regions of China

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ABSTRACT: In order to resist heavy traffic loads and reduce the risk of surface damage, rutting and settlements over time, cement-treated materials are often utilized in pavement construction in China. However, these materials exhibit drying and thermal shrinkage, resulting in cracking in the cement-treated materials. These cracking may further result in reflective cracking of the asphalt material during service. Thermal cracking is another type of cracking in the cold region of China. All these cracking generate with the micro-cracks inside the materials under tensile stress and develop with the effects of traffic and environmental loadings. As the initiated micro-cracks are invisible, it is rather difficult to predict where and when the macro-cracks will appear. In this study, the distributed optical fibre sensors were separately embedded in the cement-treated base layer, the bottom layer, and the middle layer. Then the strain distribution along with the distributed optical fibre sensors was measured every 6 months since the winter of 2018. We have found something useful for further interpretation and analysis about how the reflective cracking and thermal cracking in asphalt pavement generate and propagate.

Keywords: Asphalt pavement, reflective cracking, thermal cracking

1 INTRODUCTION

Due to its high performance(Thøgersen et al. 2004; Yeo 2008), semi-rigid base asphalt pavement has been the main form of pavement structure of high-class highways in China. However, we are still unable to thoroughly solve the cracking problems of it. Once the cracking

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generate and propagate, the overall strength of the pavement will be descended. And with the water intrusion, the performance of the pavement will be further destroyed. Normally, cement-treated materials are widely employed as the base materials for semi-rigid base asphalt pavement. Factors such as drying and thermal shrinkage of cement-treated materials can generate reflective cracking in asphalt pavement. Moreover, thermal cracking as another typical cracking usually occurs in the cold region of China. To boost the cracking resistant research, more fundamental studies are needed to better clarify how the reflective cracking and thermal cracking in asphalt pavement generate and propagate.

Many researchers were looking for research methods to evaluate reflective cracking and thermal cracking. Applications of alternative methods, such as laboratory experiment(Ji et al. 2019; Gonzalez-Torre et al. 2015), fracture mechanics(Wagoner et al. 2005; Oshone et al. 2019; Xie and Wang 2020), finite element method(Wang and Zhong 2019; Wang et al. 2018; Dave et al. 2007; Kim and Buttlar 2015) and so on, have been investigated. However, laboratory experiment has deviation comparing with the conditions of the actual pavement due to procedures and different sizes. Fracture mechanics and finite element method are both the ideal state, and some parameters are derived from the laboratory experiment. In recent years, the technology of fiber-optic cables has been introduced into civil engineering research. As a usable long-term health monitoring method, this application can provide relatively correct records, and avoid full-scale loading experiment that is expensive and service-disruptive. Skar et al. employed high-resolution fiber-optic distributed strain sensing to conclude the fundamental expressions concerning the relationship between the location of distinct strain points and the variation of soil parameters(Skar et al. 2019). Levenberg et al. studied soil support characterization in slab-on-grade constructions with fiber-optic distributed strain sensing (Levenberg et al. 2020). Furthermore, this research method has been gradually employed in pavement engineering to monitor the cracking. Xiang et al. monitored asphalt pavement based on optical fibre sensors(Xiang and Wang 2017). Their works contained the design of the optical fibre sensor, experimental investigations, and in-situ of urban asphalt pavement. Chapeleau et al. installed the optical fibers near the bottom of the asphalt layer to assess cracking based on accelerated pavement testing facility(Chapeleau et al. 2017).

Related studies indicated that the micro-cracks occurred in the initial stage of cracking formation, and coalesced into a macro-crack with the effects of traffic and environmental loadings(Ling et al. 2020). This study attempted to collect useful information to indicate the generation and propagation of macro-cracking based on Chang-Ji Expressway in the cold region of China. The technology of optical fibre sensors was employed to evaluate reflective cracking and thermal cracking. Different from the above researches, the strain of cement-treated base layer was also concerned.

2 OPTICAL FIBRE SENSORS EMBEDDED DETAILS

Based on the structure design of Chang-Ji Expressway, the layout of optical fibre sensors is shown in Figure1. The layout of optical fibre sensors in every layer is the same except for the length. More detailed information follows Table 1.

In preparation, we found the external of the optical fibre sensors was not well resistant to high temperatures. As a result of this, the optical fibre sensors were wrapped by heat-insulating materials to prevent the high temperature generated during the construction of the pavement, which would cause the melting of the external of the optical fibre sensors.

The installation process of optical fibre sensors in the cement-treated base layer was shown in Figure2. After curing, the cement-treated base layer was cut by the joint cutter following the layout of optical fibre sensors. And the cement-treated base layer in the seam was smashed and transferred manually to avoid sharp gravel generating shear force to cut the optical fibre sensors, eventually leaving a groove with a depth of 5 cm and width of 5 cm. The straightened optical fibre sensors were put into the groove and finally buried and compacted with the mixed cement mortar. Preliminary tests showed that the deformation between the cement-treated base layer and the optical fibre sensors was concerted.

Figure 1. Optical fibre sensors layout.

Table 1. Information of the layout of optical fibre sensors.

Layer	Bid-Section	d/m
Cement-treated base layer	K403-900	210
Bottom layer	K404-300	130
Middle layer	K404-300	110

Figure 2. The embedded process of optical fibre sensors in the cement-treated base layer.

The embedded process of optical fibre sensors in the bottom layer and the middle layer was similar to these procedures, as shown in Figure 3. After measurement and marking, the no compaction asphalt mixture layer was smashed into large blocks of mixed stone and transferred manually. Similarly, a depth of 5 cm and width of 5 cm groove was formed. As soon as the straightened optical fibre sensors were put into the groove, the groove would be buried manually with the remaining asphalt mixture to avoid destruction of the optical fibre sensors due to the vibration of the road roller.

Figure 3. The embedded process of optical fibre sensors in asphalt mixture layer.

And then, the survival rate of the optical fibre sensors was inspected using a red light pen. The light pen was normally at work, which indicated the optical fibre sensors had no breakage, Figure 4 depicts. This also illustrated from the side that the manual compaction had little influence on the optical fibre sensors. What's more, the joints of the optical fibre sensors were numbered and done waterproof treatment.

Figure 4. The inspection of the optical fibre sensors.

Finally, the multifiber cables were introduced into the storage box through the embedded PVC pipe. And the ODF shelf was installed. After that, every optical fibre sensor was welded to the corresponding multifiber cable through the optical cable joint case. Moreover, a steel container was set up to establish the monitor room. These procedures were described in Figure 5.

3 MONITORING EQUIPMENT

Long-distance Distributed Brillouin Optical Fibre Analyzer RP1020 made by Realphotonics was employed to collect data. More information about RP1020 is described in Table 2.

Figure 5. The procedures of optical fibre sensors assembly process.

Table 2. Information about RP1020.

Sensed distance	Spatial resolution	Sampling resolution	Precision	Swept frequency range
20 km	20 cm	5 cm	1°C/20 $\mu\epsilon^3$	10-13 GHz

4 RESULTS

The frequency shift values were obtained through RP1020, and the strain values were calculated by Formula(1). Positive numbers represent tensile strain, and negative numbers represent compressive strain.

$$Strain = \frac{\text{test frequency shift} - \text{reference frequency shift}}{\text{strain coefficient}} - \frac{\text{temperature change} \times \text{temperature coefficient}}{\text{strain coefficient}} \quad (1)$$

Illustrate: temperature coefficient—1.12MHZ/°C;

strain coefficient—0.0482MHZ/ $\mu\epsilon$;

the measured value is GHZ, converted to MHZ, 1GHZ=1000MHZ.

The optical fibre sensors in the cement-treated base layer were embedded in July 2018, and the measured values were used as the reference frequency shift. And the values measured in October 2018, March 2019, and November 2019 were taken as the test frequency shift. The temperature of the cement-treated base layer at different measurement times is displayed in Table 3. The strain values of the cement-treated base layer were calculated as shown in Figure 6, and the locations of the peak and trough strain values were marked in Figure 7. At regular intervals, the weak positions would occur the tensile strain, which was consistent with the cracking characteristic of the cement-treated base layer.

Table 3. The temperature of the cement-treated base layer.

Date	July 2018	October 2018	March 2019	November 2019
Temperature °C	30.1	12.6	11	6.8
Reference temperature °C	30.1	30.1	30.1	30.1
Temperature difference °C	0	-17.5	-19.1	-23.3

Figure 6. The strain values of the cement-treated base layer.

Figure 7. The location of peak and trough strain values of the cement-treated base layer.

The optical fibre sensors in the bottom layer were embedded in October 2018, and the measured values were employed as the reference frequency shift. Moreover, the values measured in March 2019, and November 2019 were regarded as the test frequency shift. However, the values measured in November 2019 were missing due to the destruction of the optical fibre sensors. As a result, the strain values and the locations of the peak and trough strain values were described in Figure 8 and Figure 9.

The optical fibre sensors in the middle layer were embedded in October 2018, and the measured values were employed as the reference frequency shift. Additionally, the values measured in March 2019, and November 2019 were taken as the test frequency shift. Similarly, the strain values and the locations of the peak and trough strain values were described in Figure 10 and Figure 11.

Figure 8. The strain values of the bottom layer.

Figure 9. The location of peak and trough strain values of the bottom layer.

Figure 10. The strain values of the middle layer.

Figure 11. The location of peak and trough strain values of the middle layer.

5 CONCLUSION

It was interesting to find that some high tensile strain appeared in the first several months along the traffic direction for the cement-treated base layer. In the spring of 2019, the strain of the cement-treated base layer was mostly compressive, and a few points showed as the tensile strain. In the winter of 2019, the strain of the cement-treated base layer was displayed as the tensile strain.

The strain of the asphalt mixture layer generally showed as the tensile strain. However, the compressive strain appeared at some certain points. Comparing the strain values of the middle layer in the spring with the ones in the winter of 2019, it can be seen that the changing trend of the strain values in the spring resembled the one in the winter. Moreover, the strain in the winter was higher than the ones in the spring.

Besides, the high tensile strain of the cement-treated base layer was significantly higher than that of the asphalt mixture layer. The high tensile strain indicates that the micro-cracks may develop into macro-cracks. Combined with the fact that there was no obvious cracking on the pavement, especially thermal cracking, the cement-treated base layer was more prone to micro-cracks than the asphalt mixture layer, which gradually developed into reflection cracking under the action of traffic and environmental loadings. The monitoring mission of Chang-Ji Expressway is still in progress, and the measurement will be conducted once half a year or a year, and the follow-up situation will continue to be analyzed.

ACKNOWLEDGMENTS

Thanks for the financial support of Jilin Transportation Science and Technology Projects (2017ZDGC-2-1), and the National Natural Science Foundation of China (No.51878229).

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