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Electrical signal characteristics of conductive asphalt concrete in the process of fatigue cracking

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Abstract. As a kind of intelligent materials, conductive asphalt concrete has a broad application prospect including melting ice and snow on the pavement, closing cracks in asphalt concrete, sensing pavement damage, and so on. Conductive pavement will be suffered from fatigue failure as conventional pavement in the process of service, and this fatigue damage of internal structure can be induced by electrical signal output. The characteristics of electrical signal variation of conductive asphalt concrete in the process of fatigue cracking were researched in this paper. The whole process was clearly divided into three stages according to resistance changes, and the development of fatigue damage wasn't obvious in stage I and stage II, while in stage III, the synchronicity between the resistance and damage began to appear. Thus, fatigue damage variable D and initial damage value D_0 represented by the functions of resistance were introduced in stage III. After calculating the initial damage value D_0 under different stress levels, it was concluded that the initial damage value D_0 had no noticeable change, just ranged between 0.24 and 0.25. This value represented a critical point which could be used to inform the repair time of early fatigue damage in the conductive asphalt pavement.

Keywords: conductive asphalt concrete; electrical signal; fatigue cracking; damage variable; initial damage value

1. Introduction

Adding a certain proportion of conductive material in the mixing process of asphalt mixture will make the composite has the conductive performance like conductor (García *et al.* 2009, Yang *et al.* 2013, Huang *et al.* 2009). Other than conventional asphalt concrete, the new type of conductive composites has electric conduction ability which could make removal of snow, closure of cracks and some other applications achievable (Yehia and Tua 2000, García *et al.* 2011, Wu *et al.* 2003). Therefore, this kind of intelligent materials has a broad application in the field of pavement.

Like conventional asphalt pavement, fatigue cracking caused by cumulative fatigue damage under repeated traffic load will appear in the conductive asphalt pavement (Zhi 2012, Jaeseung and Chulseung 2012, Shan *et al*. 2011). Although there are many technological means to detect the

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internal structure damage (Fan *et al.* 2013, Jo *et al.* 2013), most of these methods need to previously bury sensors in the structure. However, the changes of early internal damage could be directly sensed by electrical signal outputs if conductive asphalt concrete was used (Wu *et al.* 2005, Chung 1998, Liu *et al.*2008), thus avoiding the pavement performance degradation caused by implanted external sensors. It was showed that in the process of indirect tensile fatigue test (Liu *et al.* 2008), longitudinal electrical resistance of conductive asphalt concrete specimen increased with loading process and decreased with unloading process, and the resistance changed in the cycle with tensile strain in each loading-unloading process, which meant the resistance consistent with the strain. However, there are only few quantitative descriptions of the this phenomenon currently, and the corresponding relations between fatigue damage degree of asphalt concrete and electrical signal output has not been set up, thus it is unable to accurately judge the development of fatigue damage in the asphalt pavement.

This paper studied the electrical signal variations of conductive asphalt concrete in the process of fatigue cracking, introduced electrical signal to represent fatigue damage variable, calculated fatigue damage thresholds under different stress levels, and used this value to judge the repair time of early fatigue damage in the asphalt pavement. Through the research, relationship between fatigue damage degree of asphalt concrete and electrical signal output was established, and it would be a positive significance to the nondestructive testing and the determination of optimal repair timing of conductive pavement. Also, conductive asphalt concrete can be designed as circuit components by using its electrical characteristics. With the output of the signals, the change of pavement damage would be tested automatically.

2. Fatigue experiment

2.1 Materials

The material selected for fatigue experiment was a gap graded asphalt mixture meeting SMA requirements (i.e., the gradation of the asphalt mixture shown in Fig. 1). It has a nominal aggregate size of 9.5 mm and a binder of styrene-butadiene-styrene (SBS) modified asphalt.

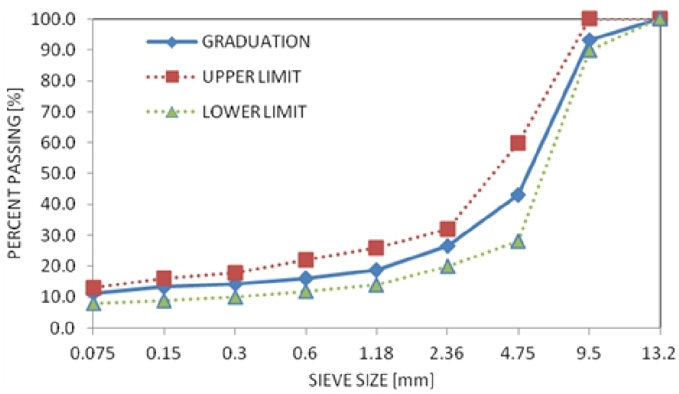

Fig. 1 Gradation of asphalt mixture

Table 1 Basic characteristics of graphite

Characteristics	Unit	Value
Maximum resistivity	Ω·cm	0.01
Nominal size	μm	30
Specific gravity	-	2.24
Apparent density	g/cm^3	0.66
Ash content	%	Less than 0.02
Moisture content	%	Less than 0.1
Specific area	m^2/g	4.5
Carbon content	%	Greater than 99.8
Particle shape	-	Irregular

Graphite with maximum resistivity 0.01 Ω•cm and nominal size 30 μm was used as the conductive fillers. The basic characteristics are shown in Table 1.

2.2 Test method

Currently, there are kinds of fatigue test method for asphalt mixture. Whereby, the bending fatigue test and indirect tensile fatigue test fatigue test are applied more widely. However, the beam specimens in the bending fatigue test are greatly influenced by some unstable factors (i.e., the degree of compaction, the size of the specimen and the deformation in the process of preparation), therefore, test results will be dispersed (Walubita *et al.* 2011), and the collection of electric signal can be difficult. By contrast, some studies of indirect tensile fatigue test indicated that this method was relatively simply operated, the stress state of specimen center adjacent parts was similar to the stress state of asphalt layer bottom, and the damage of specimen was not influenced by the surface conditions. In addition, indirect tensile fatigue test has good correlation with other fatigue test method (Wen *et al.* 2013). Therefore, indirect tensile fatigue test was chosen to simulate fatigue process of the specimens.

The content of graphite fillers was 4.6% of the volume of the aggregate. With the air void content is 4%, the optimum asphalt content was 6.1% of the total weight of the aggregate. The asphalt concrete was compacted by Superpave Gyratory Compactor (SGC). Each specimen was cylinder with 10 cm in diameter and 6.35 cm in length. Fatigue test was carried out on the MTS - 810 testing machine, test process was mainly referred to the standard of AASHTO T-322 (AASHTO 2007). Test temperature was 15℃.A half sine wave load without intermission time was applied to the specimen, and the load frequency was 10 Hz. The fatigue life was determined according to the damage point on the deformation curve. As electrodes, flexible coppers were bonded on the both sides of specimen by conductive adhesive to collect the electrical signals. Test apparatus is shown in Fig. 2.

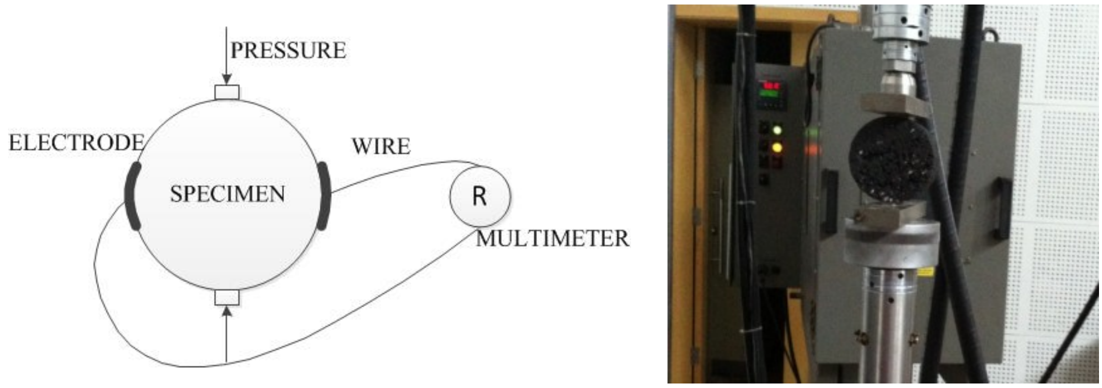

Fig. 2 Indirect tensile fatigue test

The indirect tensile stress of the specimen was calculated as follows (JTG 2011)

$$\sigma = 0.0006287P / h \tag{1}$$

Where, σ represents indirect tensile stress of the specimen, P represents the maximum test load and h represents the height of specimen.

2.3 Test results

Indirect tensile stress of the specimen σ was 1.336 MPa. To analyze the electrical signals under different stress level, the load equal to the stress ratio of 0.7, 0.5 and 0.3 was selected respectively in the indirect tensile fatigue test. The main test data is shown in Table 2.

3. Analysis and discussion

3.1 Characteristics of electrical signals

Under the stress level of 0.7σ, resistance and vertical deformation of the specimen in the process of fatigue cracking is shown in Fig. 3.

From Fig. 3, deformation curve was soared when the loads reach 7470 times, and the specimen cracked at the same time. The change of resistance in the process can be divided into three stages. In stage I, the starting point was the beginning of the loading, the specimen appeared faster compression deformation due to pressure, and the percolation network became compacted in the compression area. As a result, resistance of the specimen declined from the beginning of 1672 Ω to 821 Ω. This stage in the fatigue life is accounted for less than 10%, which can be characterized by rapid increase of deformation and quick decrease of resistance. Stage II is longer, accounts for about 30% of the whole fatigue life, and the starting point was when the resistance stopped falling. In this stage, the pressure and damage of percolation network existed side by side, pressure reduced specimen resistance, while damage increased resistance. Resistance achieved to a balanced state, there was no obvious change at this time. This stage could be described that deformation increased at a constant slow speed, resistance remained unchanged. In stage III, because the influence of the percolation network damage was more remarkable than the pressure effects, resistance began to increase, and the starting point of this stage was resistance began to consistently increase. With the accumulation of fatigue damage, the resistance increased gradually, until the fatigue cracking. This stage can be characterized by rapid synthetic increase of both deformation and resistance.

Resistance of the specimen in the process of fatigue cracking under the stress level of 0.5σ and 0.3σ is shown in Fig. 4.

As same as the characteristics of electrical signals under the stress level of 0.7σ, the two curves also can be divided into three stages according to the analysis above. The difference only lies in the fatigue life. The fatigue life of specimen was 31152 times under the stress level of 0.5σ. When the stress level dropped to 0.3σ, the fatigue life reached 143724 times.

Table 2 Electrical signals under different stress level

Time [s]	R [Ω]		
	0.7σ	0.5σ	0.3σ
0	1672.0	1681.0	1672.0
100	1099.5	1364.2	1564.2
500	821.0	1262.6	1462.6
1000	884.0	1101.1	1371.1
2000	821.0	1019.5	1299.5
3000	827.0	996.4	1186.4
6000	1802.7	894.8	1074.8
10000	N/A	870.7	921.0
15000	N/A	894.7	884.0
17000	N/A	1187.0	871.0
20000	N/A	1573.0	872.0
22000	N/A	2053.0	865.0
27000	N/A	2731.0	892.0
30000	N/A	3400.0	834.0
32000	N/A	3981.6	814.0
40000	N/A	N/A	852.0
50000	N/A	N/A	843.0
62000	N/A	N/A	991.0
70000	N/A	N/A	1164.0
80000	N/A	N/A	1274.0
90000	N/A	N/A	1480.0
100000	N/A	N/A	1602.7
130000	N/A	N/A	2434.5
140000	N/A	N/A	3985.1
150000	N/A	N/A	N/A

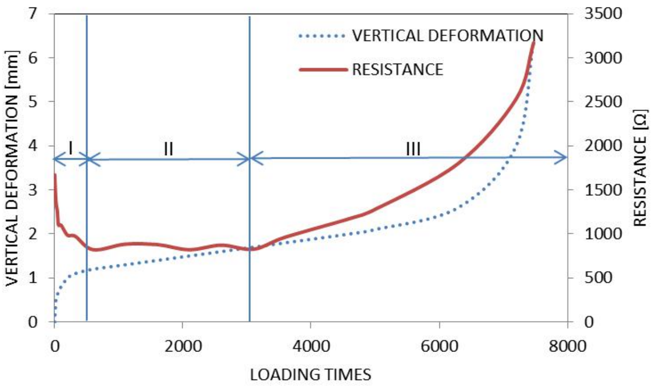

Fig. 3 Characteristics of electrical signals under the stress level of 0.7σ

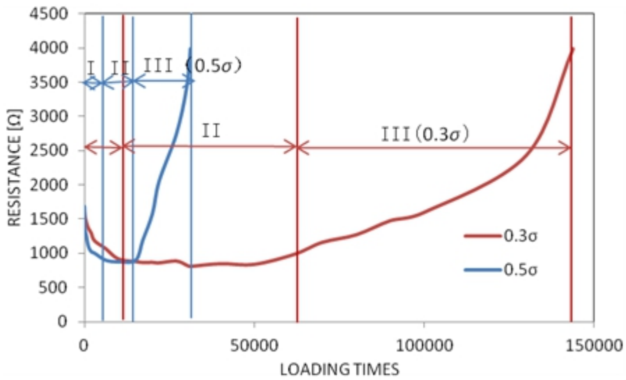

Fig. 4 Characteristics of electrical signals under the stress level of 0.5σ and 0.3σ

3.2 Fatigue damage variable represented by electrical signal

From analysis above, in stage I, specimen became denser under pressure, and no damage appeared. In stage II, resistance didn't decrease with the compaction of the specimens, suggesting that fatigue damage had already appeared in the interior of specimens while the damage evolution was not dominant. In stage III, the synchronicity between the resistance and damage began to appear, the damage evolution began to be dominant in the specimen deformation, micro cracks in specimens started to develop, and the increase of resistance and the development of damage were consistent, thus, the fatigue damage variable of this stage could be represented by Eq. (2).

$$D = R / R_f \tag{2}$$

Where, D is damage variable, R is resistance in stage III, R_f is the resistance when specimen is cracked.

Defined N_3 as the loading times when stage III started, N as loading times, N_f as total loading times. Through calculation and analysis, corresponding relations between $(N\text{-}N_3)$ / $(N_f\text{-}N_3)$ and D under three kinds of stress level is shown in Fig. 5.

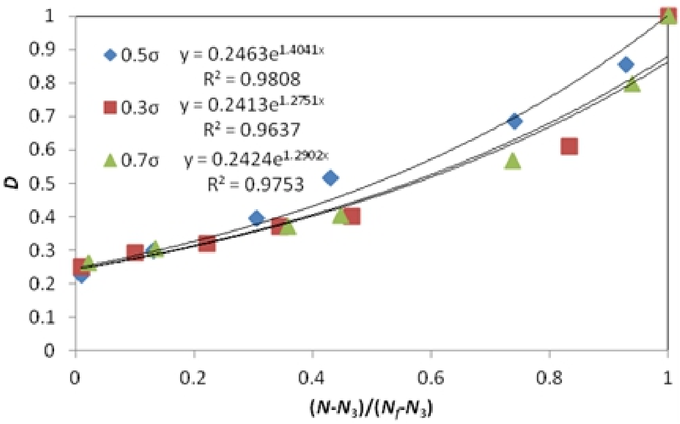

Fig. 5 Fitting curves of resistance in stage III under three kinds of stress level

Seen from Fig. 5, although fatigue curves of asphalt concrete specimens under three kinds of stress level were different, these three regression curves were essentially coincident. The correlation coefficient R^2 of test data and the regression results were more than 0.96, and it was showed that in stage III, the damage variable represented by electrical signal under different stress level had the same change rule, damage variable D could be expressed as the following form

$$D = D_0 \cdot e^{\lambda\left(\frac{N-N_3}{N_f-N_3}\right)} \quad (N>N3) \tag{3}$$

Where, D_0 is the initial damage value, namely the ratio of resistance in the beginning of stage III and R_f, and λ is a constant.

3.3 The fatigue damage threshold value

Based on the regression data in Fig. 5, the respective parameters of Eq. (3) could be obtained, as shown in the Table 3.

Although the stress level was different, the initial value of damage variable D_0 had no noticeable change, just ranged between 0.24 and 0.25.When damage variable D reached this value, the damage cracks gradually dominant, lead to the gradually broken of percolation network, as a result, resistance increased gradually. As the damage variable D increased to 1, meaning that the specimens had been destroyed and the bearing capacity of structure was lost.

Table 3 Respective parameters under three kinds of stress level

Stress level	D_0	λ	R^2
0.3σ	0.241	1.275	0.964
0.5σ	0.246	1.404	0.981
0.7σ	0.242	1.290	0.975

Initial value of damageD_0 represented a critical point when the damage development in the evolution process of percolation network began to dominate, resistance began to increase in the process of fatigue cracking. The calculation results of initial damage value D_0 showed that for the same kind of conductive asphalt concrete, no matter how much stress was applied in the fatigue tests, the critical points when the percolation network began to suffer from damage were the same, and resistance also began to increase in the same location nearby.

It was found that the damage timing of conductive asphalt concrete in the fatigue test appeared in the position of 10% around of the whole fatigue life (the corresponding damage variable value was 0.24 to 0.25), at this point, the resistance no longer fell with the compression deformation of specimens, which meant that fatigue damage inside specimens began to appear and accumulate, and when accumulated to a certain degree, damage began to occupy the leading role in the percolation network restructuring, the specimen resistance began to increase, the macro-fracture also gradually appeared. Combined with the previous analysis, the initiative repair time of conductive asphalt concrete should be chose in the stage when fatigue damage accumulates, namely stage II in Figs. 3 and 4, in this stage, the resistance had no obvious change and was stable at a fixed interval. Through the conclusion of Table 3, it was known that for the same kind of conductive asphalt concrete material, the damage value D_0 represented by electrical signal was fixed, namely for the graphite/SMA10 complex system, when the damage variable D was between 0.24 and 0.25, active recovery technology such as self-healing could be considered to be used to repair early fatigue damage.

The conclusion above was based on a certain fatigue loading patterns and a specific mixture. If these two conditions were changed, D_0 might also change. This argument need to be investigated further.

4. Conclusions

1. Characteristics of electrical signal variation of conductive asphalt concrete in the process of fatigue cracking was researched, it was showed that the resistance change of the specimen during the entire process of fatigue testing can be divided into three stages, corresponding to resistance dropping (I), resistance smoothly fluctuating (II), and resistance rising (III).

2. In stage III, fatigue damage variable represented by electrical signal was introduced, and initial fatigue damage values D_0 under different stress levels was calculated. D_0 represented a critical point when damage began to occupy the leading role in the evolution process of percolation network, and resistance began to increase in fatigue process.

3. Under different stress levels, the initial fatigue damagevaluesD_0 had no noticeable change, just ranged between 0.24 and 0.25, namely for the same kind of conductive asphalt concrete, no matter how much stress was applied in the fatigue test, the resistance began to increase in the same location nearby. This value could be used to provide reference for the judgment of repair time of early fatigue damage in asphalt pavement.

5. Prospect

By using the co-evolution relationship between fatigue damage degree of asphalt concrete and electrical signal output, conductive asphalt concrete can be designed as circuit components in the pavement, and the damage in the structure would be tested automatically and intelligently.

Acknowledgements

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