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Resistivity-temperature Characteristics of Conductive Asphalt Concrete

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Abstract: The changes of resistivity of conductive asphalt concrete at different temperatures were studied, and positive temperature coefficient (PTC) model was established to estimate the influence of temperature on the resistivity quantitatively, which eliminated the interference with conductivity evaluation brought by temperature variation. Finally, the analysis of temperature cycling test results proves that the changes of percolation network structure caused by temperature variation prompt the emergence of PTC of conductive asphalt concrete.

Key words: conductive asphalt concrete; electrical resistivity; positive temperature coefficient; percolation network

1 Introduction

In the mixing process of asphalt concrete, adding a certain proportion of conductive material could make the composite asphalt concrete conductive as conductor[1-3]. This new type of conductive composites had electrical and thermal conduction ability which conventional asphalt concrete lacked of, and when it was used as pavement materials, this ability could be used to achieve the purpose of snow melting, damage diagnosing and crack closing, which made it have broad application prospects[4-6].

Conductive asphalt concrete was particularly sensitive to ambient temperature, and the conductive properties of asphalt concrete usually changed with ambient temperature[7,8]. Previous research had shown that positive temperature coefficient (PTC) effect that the resistance of conductive asphalt concrete would increase with the rising of temperature and decrease when temperature dropped had been observed near the percolation threshold[9]. Affected by alternation of day and night as well as the change of seasons, asphalt pavement was experiencing heating-cooling cycles. Therefore, when detecting the conductive asphalt pavement[10-12], the interference with test value brought by temperature variation should be taken into account. Only then could the damage evolution in the pavement be determined accurately. The corresponding relationship between temperature and conductivity of the conductive asphalt concrete has not been established in previous studies, so that the effects of PTC could not be evaluated quantitatively.

This paper studied the resistivity characteristics of conductive asphalt concrete at different temperatures. PTC model was established to evaluate the influence of temperature on resistivity. In the temperature cycling test, resistivity changes of conductive asphalt pavement was observed, and the mechanism of action by temperature on resistivity was analyzed.

2 Experimental

2.1 Materials

The material selected for fatigue experiment was a gap graded asphalt mixture meeting SMA 10 requirements (*i e*, the gradation of the asphalt mixture is shown in Fig.1). It had a nominal aggregate size of 9.5 mm and a binder of styrene-butadiene-styrene (SBS) modified asphalt.

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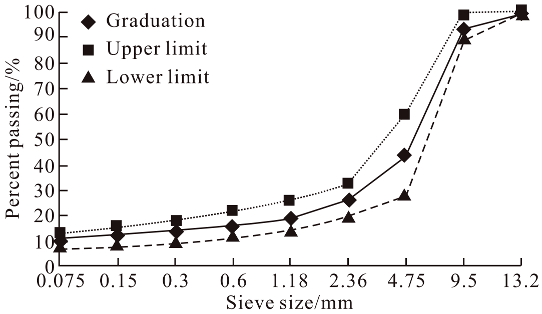

Fig.1 Gradation of aggregate

Table 1 Basic characteristics of carbon black

Characteristics	Unit	Value
Maximum resistivity	Ω · cm	8
Nominal size	nm	12
Specific gravity	g/cm^3	1.8
Apparent density	g/cm^3	0.12
Ash content	%	Less than 0.3
Moisture content	%	Less than 0.5
Specific area	m^2/g	1250
Pore volume	cm^3/100g	480-510
pH	-	6.5-7.5

Carbon black with maximum resistivity of 8 Ω·cm and nominal size of 12 nm was used as the conductive fillers. The basic characteristics are shown in Table 1.

2.2 Selection of carbon black content

At first, there were eleven types of mixtures prepared with the carbon black at 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, and 10% of the total aggregate content. The percentage of carbon black was calculated based on the total weight of the aggregate. No separate mix designs were performed for the mixtures containing carbon black. When higher percentages of carbon black were applied, adjustments were made to reduce the fine aggregate portion from the control mix so that the mixtures with conductive fillers had a similar gradation and asphalt content to the ones of the control mixture[13]. With an air void content of 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 a cylinder with 10 cm in diameter and 6.35 cm in length.

A JWY-30F DC stabilized power supply and two UT33C digital multimeters were employed to measure electrical resistivity. The electrodes made of copper sheets were stuck to the cross profiles of the specimens by conducting resin (see Fig.2). The DC stabilized power supply and digital multimeters were connected to the electrodes by the wires.

Contact resistance was eliminated according to the previous method[14]. The calculated resistivity ρ with different carbon black contents Φ is shown in Fig.3.

As can be seen from Fig.3 , the resistivity of asphalt concrete decreased with the increase of the content of carbon black. In a narrower area where the content of carbon black was between 5%-8%, the change of resistivity reached more than 3 orders of magnitude. This area could be defined as "percolation area", and the percolation threshold appeared here[15]. The carbon black contents selected for resistivity-temperature tests, 5%, 6%, 7%, and 8% of the total aggregate content, was in this area.

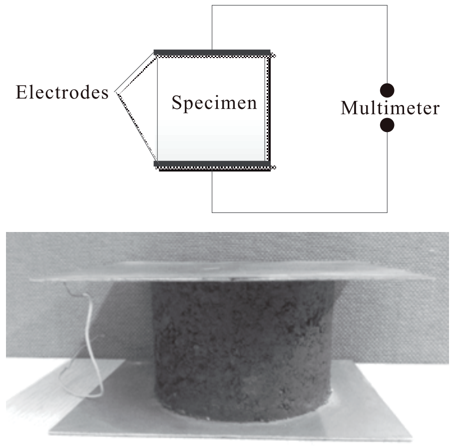

Fig.2 The two-electrode method

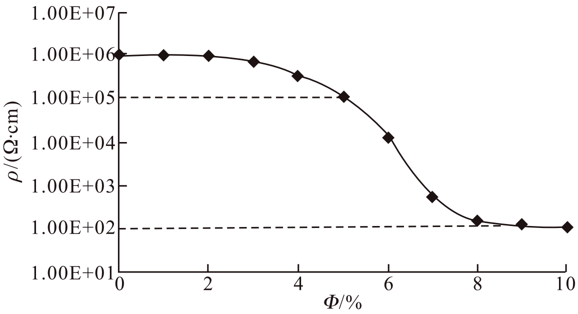

Fig.3 Calculated resistivity with different carbon black contents

2.3 Resistivity-temperature characteristics with different carbon black contents

The resistivity of the selected specimens was tested at different tempetatures. At first, resisitivity was tested in the process of cooling of the specimens after molding. Then, when the temperature of the specimen was reduced to 70 ℃, the mixture had been hardened. In order to ensure that temperature was uniformly distributed, the specimen was put in the calorstat at the fixed temperature for 6 h before resistivity test. So the testing temperature can be divided into two parts: 100-70 ℃ (section a, natural cooling), and 70-(−20) ℃ (section b, calorstat control).

Resistivity-temperature characteristics with different carbon black contents can be seen in Fig.4.

As shown in Fig.4, with the decrease of temperature, all the resistivity gradually lowerd,

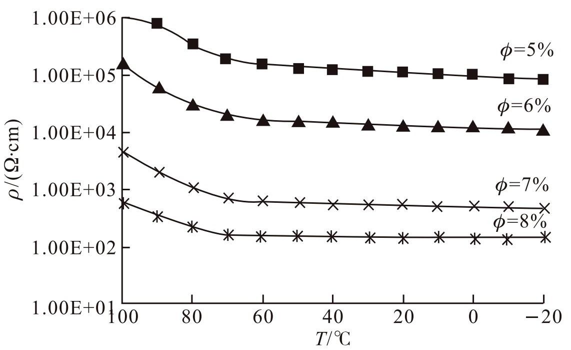

Fig.4 Resistivity-temperature characteristics with different carbon black contents

showing the phenomenon of positive temperature coefficient (PTC).

3 Establishment of PTC model

In order to compare the temperature dependence of the different specimens, 100 ℃ was set as limit temperature T_0, relative temperature t was defined as $(T_0-T)/T_0$. The resistivity with different relative temperatures t is shown in Fig.5.

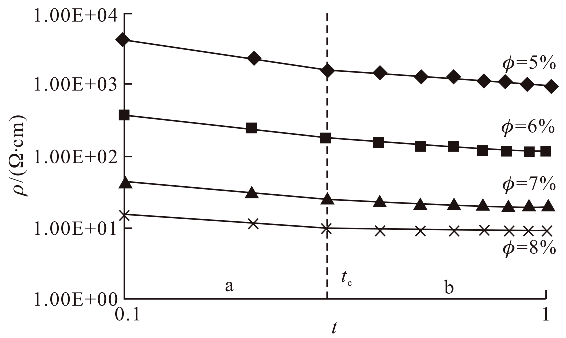

Fig.5 Resistivity with different relative temperature t

From Fig.5, under the condition of any carbon black contents, when the relative temperature t located near the asphalt softening point t_c, a turning point would appear on the resistivity-temperature curve. As a result, the declining trend became slower.

In Fig.5, the logarithm of resistivity on both sides of the relative temperature respectively had a linear relationship. All the curves could be classified as two sections (a and b) according to the slopes. The content of carbon black only had an effect on the slope of the straight line. Within these two sections, the temperature dependence of the specimens was different, which can be respectively represented by the following forms:

$$\rho_a=At^{-a} \quad (t<t_c) \tag{1}$$

$$\rho_b=Bt^{-b} \quad (t>t_c) \tag{2}$$

where, ρ_a is the resistivity in section a, Ω·cm; ρ_b is the resistivity in section b, Ω·cm.

Regressing test data according to the formulas above, the values of four parameters A, B, a, and b can be obtained. The parameters with with different carbon black contents are shown in Table 2.

Table 2 Parameters with with different carbon black contents

Φ/%	A/(Ω·m)	a	B/(Ω·m)	b
5	320 88	1.474	983 88	0.507
6	507 5.6	1.145	121 90	0.359
7	246.8	0.842	518.21	0.175
8	91.04	0.474	145.57	0.065

Using the fitting values of the parameters mentioned above, resistivity-temperature characteristics of conductive asphalt concrete with specific carbon black content can be expressed very well. All the values of parameters decreased regularly with the increase of carbon black content.

For the convenience of calculation, the carbon black relative content φ was defined as Φ/Φ_{c1}, where Φ_{c1}=4.9%. The relationship between φ and the four parameters is shown in Fig.6.

From Fig.6, the four parameters A, B, a, b, and φ satisfied the following equations:

$$A=A_0\varphi^{-j} \tag{3}$$

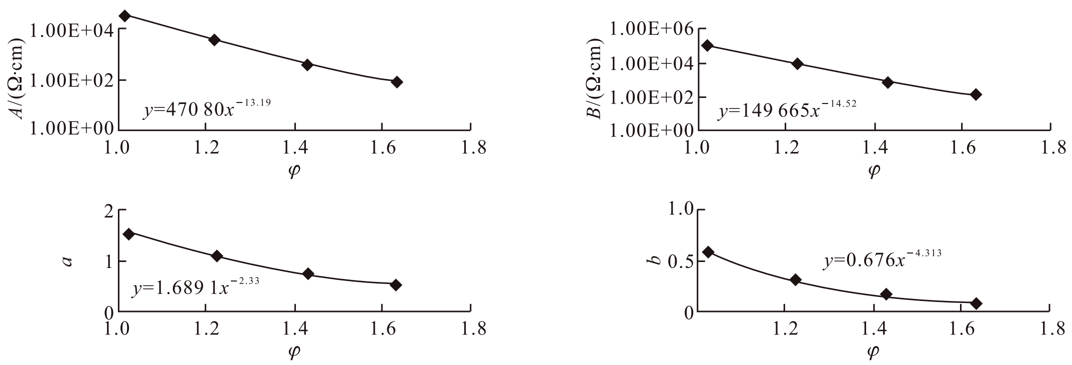

Fig.6 Relationship between ϕ and the four parameters

$$a=a_0\varphi^{-k} \tag{4}$$

$$B=B_0\varphi^{-l} \tag{5}$$

$$b=b_0\varphi^{-m} \tag{6}$$

According to the regression equations in Fig.6, the values of parameters A_0, j, a_0, k, B_0, l, b_0, and m can be obtained, as shown in Table 3.

Table 3 Values of parameters

A_0 /(Ω·cm)	j	a_0	k	B_0 /(Ω·cm)	l	b_0	m
47080	13.19	1.6891	2.33	149665	14.52	0.676	4.313

Putting the Eqs.(3)-(6) into Eqs.(1) and (2), PTC modle can be obtained as follows:

$$\rho_a = A_0\varphi^{-j}t^{-a_0\varphi^{-k}} \qquad (t<t_c) \tag{7}$$

$$\rho_b = B_0\varphi^{-l}t^{-b_0\varphi^{-m}} \qquad (t>t_c) \tag{8}$$

From the preceding formulas, this modle was based on the statistical analysis of test data. In this model, resistivity is mainly affected by the temperature and the carbon black content. According to the fitting values of the parameters in Table 2, resistivity with the changes of temperature and the carbon black content can be calculated by PTC modle, as shown in Fig.7.

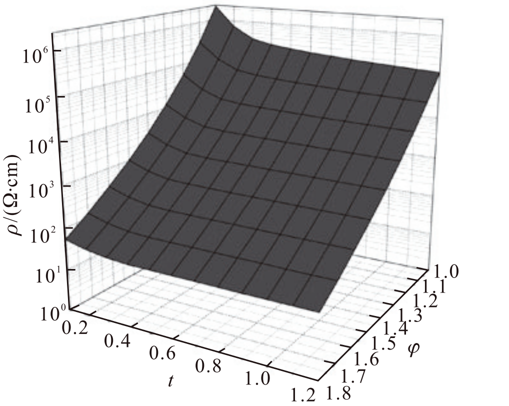

Fig.7 Resistivity with the changes of temperature and the carbon black content

As can be seen from the 3D graphics above, when the relative temperature and the carbon black content increased respectively, the resistivity of conductive asphalt concrete decreased. When the two parameters increased at the same time, the downward trend of resistivity would be more obvious.

If the conductive filler type or initial percolation network changes, parameters in PTC model have corresponding changes. Parameters a and b in graphite-SMA composite system were smaller than that in carbon black-SMA composite system, which indicated that the downward trend of resistivity-temperature curve of graphite-SMA composite system was less apparent than that of carbon black-SMA composite system. And parameters a and b in graphite-SMA 13 composite were smaller than that in graphite-SMA 10 composite, which was caused by the difference of initial percolation networks. But with the change of conductive filler type and initial percolation network, all the resistivity-temperature curves dropped with the increase of conductive filler content and the changes of resistivity with temperature had similar characteristic that the resistivity-temperature curve had a turning point around the softening point of asphalt. It could be concluded that the physical origin of PTC effect is independent of the conductive filler type and initial percolation network.

PTC model was a statistical model, which established the relationship between the resistivity and the temperature, but the model could not involve the mechanism of action by temperature on resistivity.

4 Mechanism of action by temperature on resistivity

The field temperature environment of pavement was simulated, with two heating and cooling processes, in which temperature varied between 60 ℃ and (−20) ℃ were enforced on the specimen. The resistivity-temperature characteristics are shown in Fig.8.

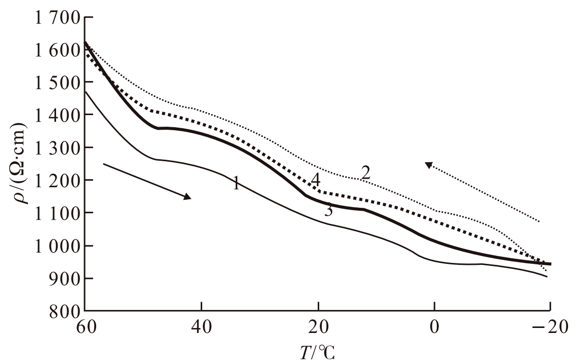

Fig.8 Resistivity-temperature characteristics in temperature cycle (Φ=6.7%)

In Fig.8, soild line represents the cooling process, and dotted line represents the heating process. In the process of temperature cycle, heating and cooling processes represented by the two curves were not coincidence. In the first round of the thermal cycle, resistivity first reduced in the cooling process and then increased with the increase of temperature. These two curves overlaped at (−20) ℃. After that, the heating curve deviated from the cooling curve. Then at 60 ℃ the heating curve overlaped the next cooling curve in the second round, this cooling curve continued to deviate from the last heating curve. This showed that the temperature cycle had certain influence on the resistivity. Resistivity could not recover to the original value after temperature cycle and the resistivity was irreversible. But compared to the first round of thermal cycle, the deviation degree in the second round was much smaller. It is shown that the resistivity-temperature characteristics of conductive asphalt concrete would be stabilized after several temperature cycles, the interference of temperature cycle would be smaller.

In the process of temperature variation, due to the uncertainty of molecular thermal motion, the contact state of conductive particles and asphalt binder will be randomly changed. Changes of the relative position of conductive particles induced percolation network changes. In macroscopic view, it is the rise and fall of the conductivity of conductive asphalt concrete. This is the reason why the resistivity-temperature curves had a turning point around the softening point of asphalt. When temperature is lower than the softening point of asphalt, as conductive filler and asphalt have different coefficients of thermal expansion, in the process of increasing temperature, the difference of the degree of volume expansion between two phase results in the increase of distance between conductive particles. Then some conductive channels are cut off and the percolation network is damaged to some degree, which makes the increase of resistance of composite system. When temperature exceeds the softening point of asphalt, thermal motion of the molecules in carbon black-SMA composite system is exacerbated. A part of infinite conductive clusters decomposed and this leads to the break of conductive channels and the increase of the resistance of the whole system.

Conductive particles at a certain temperature were combined to form a local stable state. After a temperature cycle, this part of conductive particles might be moved to another area, this caused resistivity-temperature characteristics has poor repeatability in the process of temperature cycle. However, with the increase of temperature cycles, the conductive particles removal also tended to a state of repeatable. In macroscopic view, the heating and cooling curve tended to coincide.

5 Conclusions

a) The resistivity characteristics of conductive asphalt concrete at different temperatures were analyzed. As the temperature decreased, all the resistivity gradually lowerd, the phenomenon of positive temperature coefficient (PTC) was presented.

b) Under the condition of any carbon black contents, when the relative temperature t located near the asphalt softening point t_c, a turning point would appear on the resistivity-temperature curve. Resistivity-temperature curves could be classified into two sections according to the slopes, then PTC model can be established based on the statistical analysis of test data. And the influence of conductive filler type and initial percolation network on PTC model was discussed. So resistivity-temperature characteristics can be evaluated quantitatively.

c) Temperature cycle had certain influence on the resistivity, resistivity could not return to the original value after temperature cycle, and the resistivity was irreversible. But resistivity-temperature characteristics of conductive asphalt concrete would be stabilized after many temperature cycles. With further analysis, the changes of percolation network structure caused by temperature variation prompted the emergence of PTC of conductive asphalt concrete.

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