Research on Asphalt Mixture Based on Thermophysical Properties

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ABSTRACT: In China shear rutting is main one of highway diseases, and extreme high temperature event has taken place more frequently in summer. In view of shear rutting and urban heat island, the article puts forward the way we can reduce pavement temperature by altering thermophysical property of asphalt pavement actively. Based on the heat transfer mechanism, it showed evident correlation between thermophysical property of aggregate and theunophysical property of asphalt mixture by Williamson models, and several pieces of samples with different ratios of the ceramics, pottery sand and granite were verified by a plane heat source method with constant heat rate. After that, the impact of thermodynamic parameters of pavement material and temperature of pavement structure was researched through several representative temperature field models, and the samples were tested outside in the day. The results show that pavement temperature will be reduced by lower thermal conductivity, especially in the bottom. The technology has been applied in a new highway in China, and the feasibility of engineering application has been analyzed. The result shows that we can reduce negative effect of urban heat island and keep pavement temperature in extreme climate through that.

KEY WORDS: Road engineering, thermophysical property, asphalt mixture, rutting, hot island effect.

1 PREFACE

Asphalt mixture is a kind of viscoelastic material with strength and property changing with temperature, thus actual bearing capacity of pavement structure changing with temperature. Different forms of damage will be caused to asphalt pavement under different temperature, for example, high temperature will cause asphalt rut, and low temperature will lead to pavement rind, etc. Traditional solution is to increase temperature of pavement material and strength under low temperature passively to resist damage caused by temperature, etc. If temperature of pavement is under control and is far away from high temperature area, asphalt rut could be largely decreased, and performance and life of asphalt pavement could be increased. Meanwhile, applying “low temperature” asphalt pavement to urban roads could decrease urban “Heat Island Effect” caused by traditional asphalt pavement.

This essay studies on thermophysical property of asphalt mixture to explore relationship between aggregate, asphalt mixture and temperature of asphalt pavement, change thermophysical property of pavement by replacing traditional aggregate with raw materials which possess thermal resistance property —spray thermal resistance heat-reflective coating, analyze temperature variations of pavement structure, and put forward feasibility of changing asphalt pavement temperature field actively.

2 THERMOPHYSICAL PROPERTIES RELATION BETWEEN AGGREGATE AND MIXTURE

2.1 Calculation and Analysis of Theoretical Model

Study on thermophysical properties relation between aggregate and mixture originates from theoretical study on asphalt pavement temperature field. Few studies have been carried out by scholars at home and abroad. This essay analyzes thermophysical properties relation between aggregate and asphalt mixture from theoretical and experimental aspects. Formula of thermal conductivity of asphalt mixture and composite materials in Heat Transfer are put forward by Williamson in 1972 for theoretical analysis.

In 1972, Williamson studies on thermal conductivity of asphalt mixture and put forward formula 90% accuracy, that is:

$$k_m = (k_a)^m \cdot (k_b)^n \cdot (k_v)^p \cdot (k_w)^q \qquad (1)$$

Among which,

k_m — Thermal conductivity of asphalt mixture

k_a — Thermal conductivity of aggregate

k_b — Thermal conductivity of binder

k_v — Thermal conductivity of air

k_w — Thermal conductivity of water

m, n, p, q— volume percentage of aggregate, binder, air and water in mixture by decimal.

Put proposed k_a,m=0.78,n=0.17,p=0.05,q=0,k_b=0.74W/m·℃ and k_v=1.569×10^{-5}W/m·℃ into formula (1), we can get k_m. Relation between thermal conductivity k_a of aggregate and thermal conductivity k_m of asphalt mixture refers to in Figure 1.

Calculating through Williamson theoretical formula**,** we can conclude that linear relation exists between thermal conductivity of aggregate and mixture, so thermal conductivity of asphalt mixture could be changed if that of aggregate is changed.

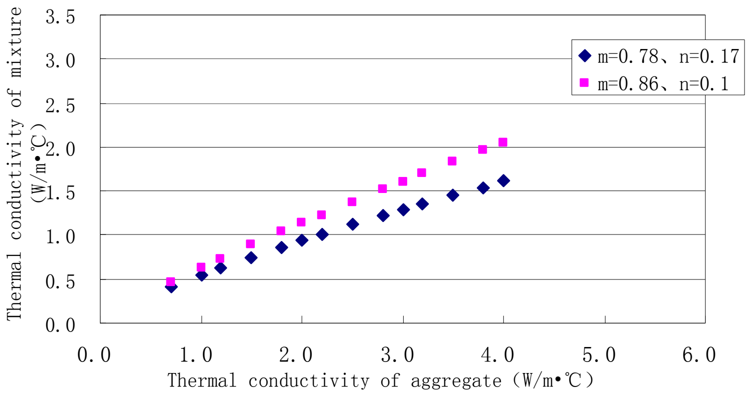

Figure 1: Relation between thermal conductivity of aggregate and thermal conductivity of asphalt mixture

2.2 Test Analysis

Considering that pavement is heated on single side of the plane and its trialability through test, etc., this experiment applies plane-source method with constant heat rate, which is a kind of unstable test. It aims to test thermal diffusivity of asphalt mixture and its thermal conductivity, and calculate specific heat capacity, based on temperature field variation law inside semi-infinite object within constant heat flow boundary.

When surface of infinite isotropic objects with initial temperature t_0 is heated by heat flow with constant heat rate, we can get temperature field by the following thermal conductivity differential equation.

$$\frac{\partial \theta}{\partial \tau} = \alpha \frac{\partial^2 \theta}{\partial x^2} \tag{2}$$

Initial condition： $\tau = 0$， $\theta_{\text{int}} = 0$

Boundary condition： $x = 0$ ， $q = -\lambda \left(\frac{\partial \theta}{\partial x} \right)_{x=0} = 0$

Among which,

θ— Surplus temperature，based on τ_0. For example，surplus temperature of the point δ_1 away from surface at τ_1 time is $\theta_{(\delta_1,\tau_1)} = t_{(\delta_1-\tau_1)} - t_0$

q— Heat flow density，W/m2；

λ— Thermal conductivity，W/（m·℃）

Solve formula（2）under initial and boundary condition, we can get：

$$\theta_{(x,\tau)} = \frac{2q}{\lambda}\sqrt{\alpha\tau} \cdot ierfc\left(\frac{x}{2\sqrt{\alpha\tau}}\right) \tag{3}$$

Among which,

$ierfc\left(\frac{x}{2\sqrt{a\tau}}\right)$—a single variable of Guass Complementary Error Function

According to formula（3）, if initial temperature of object is t_0, heat by constant heat flow q at 0 time, test surface temperature $\theta_{(0,\tau_1)}$ at τ_1 time and temperature $\theta_{(\delta_1,\tau_2)}$ is δ_1 away from surface at τ_2 time（δ_1 is the location of setted measuring point）, then thermal diffusivity and thermal conductivity of the object could be got through calculation.

If $\mu = \frac{\delta_1}{2\sqrt{\alpha\tau_2}}$, then thermal diffusivity and thermal conductivity λ are:

$$\alpha = \frac{\delta_1^2}{4\mu^2\tau_2} \quad ,\lambda = \frac{2q}{\theta_{(0,\tau_1)}}\sqrt{\frac{\alpha\tau_1}{\pi}}$$

We can get thermal diffusivity *a* and thermal conductivity λ through calculation after getting $\theta_{(0,\tau_1)}$, $\theta_{(\delta_1,\tau_2)}$, τ_1 and τ_2.

This experiment is proposed to carry out thermophysical properties test toward seven different materials and their asphalt mixture to test whether they will change if composite materials change. Specific test results refer to Figure 1.

Table 1 Result of Thermophysical Parameter of Asphalt Mixture

	A	B	C	D	E	F	G
Category / Parameter	granite(1)+ pottery sand	granite(2)+ pottery sand	granite(3)+ pottery sand	pottery sand+ ceramics	normal aggregate(1)	normal aggregate	ceramics+ normal aggregate
a（m^2/h）	0.00122	0.00139	0.0012	0.0005	0.00241	0.00118	0.00077
λ（W/m·℃）	0.872	0.867	0.856	0.685	0.838	1.022	0.736

Results show that changing aggregates of asphalt mixture could change thermophysical parameter of asphalt mixture. Among which, F is common asphalt mixture with thermal conductivity 1.02℃ or so, while thermal conductivity of D is 0.69W/m·℃ which is least of above seven. Thermal conducting capacity of one mixture is almost 3 times that of the other. We can conclude that changing aggregate will exert much influence on thermal conductivity of asphalt mixture.

3 RELATION OF THERMOPHYSICAL PROPERTIES OF ASPHALT MIXTURE AND ASPHALT PAVEMENT TEMPERATURE

Study on theoretical temperature field consists of study on thermophysical parameter of asphalt mixture, most of which originates form one dimension thermal conducting equation in

Heat Transfer. This essay analyzes relation between thermophysical properties of asphalt mixture and asphalt pavement temperature from theorical and experimental aspects. Theoretical analysis applies one dimension heat transfer model and pavement temperature field of Barber model.

One dimension thermal conducting equation in Heat Transfer is:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial z^2} \tag{4}$$

which is solution equation（4）, new parameter $u = \frac{z}{2\sqrt{at}}$ could be introduced into, then differential equation could be got through simplification.

$$\frac{d^2T}{du^2} + 2u\frac{dT}{du} = 0 \tag{5}$$

And temperature distribution equation in different depth in imaginary isotropic half-space object could be got， which is,

$$T_z = (T_c - T_b)\frac{2}{\sqrt{\pi}}\int_0^u e^{-u^2}du + T_b \tag{6}$$

Among which,

T_c— Initial temperature of pavement（℃）;

T_b— Pavement surface temperature caused by heat source function（℃）;

z— Distance of temperature calculating point from pavement surface（m）, 0≤z≤h1;

a —Thermal diffusivity（m2/h）;

t—Temperature function and time;

If integral value is F(u)= $\frac{2}{\sqrt{\pi}}\int_0^u e^{-u^2}du$, then,

$$T_z=F(u)(T_c-T_b)+T_b \tag{7}$$

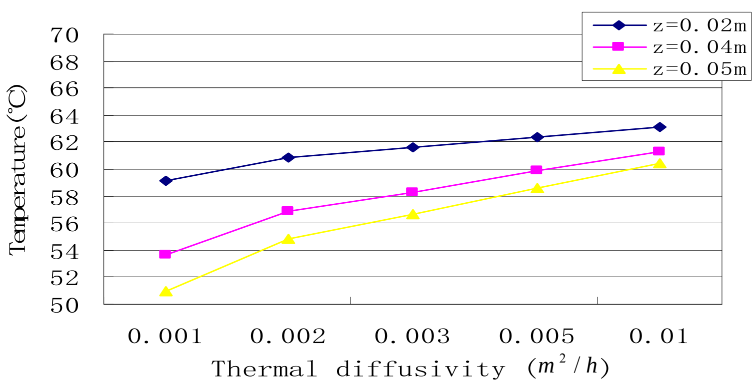

Figure 2 Relation between thermal diffusivity and temperature

Through calculation, relation between thermal diffusivity and temperature is shown in Figure 2. Through model calculation and analysis in Heat Transfer, we can get that temperature of pavement structure in certain depth increases along with thermal diffusivity. As it goes deeper, temperature of pavement structure increases along with increasing amplitude of thermal diffusivity. It shows that different thermophysical properties could change temperature field of asphalt pavement effectively.

When calculating highest temperature 0.02m below pavement through second Barber model, put z=0.02 and sin(x)=1 into formula (8), then:

$$\theta_{max} = T_a + R + \frac{H}{\sqrt{(H+K)^2 + K^2}}(0.5T_r + 3R)e^{-0.02K} \tag{8}$$

Among which,

H— Ratio of convection coefficient to material conductivity coefficient, which is：

K— Hot property comprehensive parameter of pavement materials，

R— Average increment when temperature increases to effective temperature caused by radiant heat（℃），net loss of estimated effective radiation is about 1/3 on average；

T_r—Daily variation amplitude of temperature（℃）

We can get relation between asphalt mixture and asphalt pavement temperature field by fixing other variables and changing thermal conductivity of mixture, calculation results refer to Figure 3.

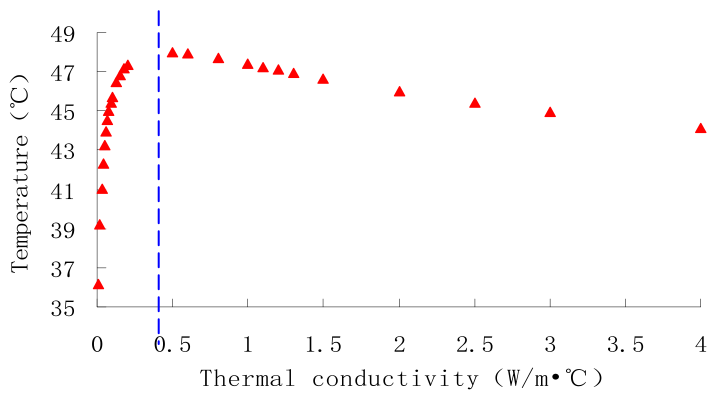

Figure 3 Relation between thermal conductivity and temperature

Scholars at home and aboard having carried out analysis about temperature field of asphalt mixture with different thermophysical properties basically think that there is little influence upon asphalt pavement temperature field when changing thermophysical properties of asphalt mixture. Thermal conductivity λ of most asphalt mixture is 1W/m·℃ or so. Seen from above figure, thermal conductivity has little influence upon temperature of asphalt pavement near this point and slope of regression curve is only K=-1 or so, which also prove that little influence is exerted upon temperature field of asphalt pavement when changing thermal conductivity of asphalt mixture individually within small area. However, if thermal conductivity λ is less than 0.5W/m·℃, both trend and slope of curve will have changed greatly. Opposite to the situation when λ is greater than 1W/m·℃, if λ is less than 0.5W/m·℃, maximum temperature of pavement will decrease greatly in greater slope（about K=48）along with decrease of thermal conductivity. And λ will change pavement temperature obviously.

Relation curve between thermal conductivity and temperature is parabolic curve with main reasons as follows:

1）Referring to Barber temperature field model, λ exists in both quadratic term and extracted term, so relation curve between λ and pavement maximum temperature could takes on second degree parabola.

2）Thermal conductivity and thermal diffusivity are in direct proportion, so thermal diffusivity increases when thermal conductivity increases. Thermal diffusivity accelerates spread of heat, causing heat absorbed by upper layer spreads downward vertically and temperature inside pavement decreases, thus thermal conductivity increases when pavement temperature decreases. However, when thermal conductivity is rather small, pavement materials possesses the function similar to heat insulation material, preventing vertical spread of heat along pavement, therefore, pavement temperature will decrease rapidly along with decrease of thermal conductivity.

To sum up, through theorical calculation with heat transfer model and Barber model, asphalt pavement temperature field could be changed effectively through changing thermophysical property of asphalt mixture.

4 OUTDOOR TEST

In order to prove influence of thermophysical properties of asphalt mixture toward pavement temperature, make rut trial pieces using above seven kinds of materials and their combination. Test and prove it outdoor.

4.1 Preparation of Trial Pieces

The experiment applies middle value among AC-16 grading. Asphalt is 70# base asphalt, and aggregate consists of pottery sand, ceramics, basalt, granite, etc. Match different materials in certain proportion and roll 12 times with edge runner mill to make 7 rut trial pieces as simulation pavement to measure variable characteristics under actual temperature.

4.2 Test Platform

Test platform is mainly composed of two parts, e.g. temperature collection system composed of temperature sensor, etc. and data collection system composed of computer system and data collection software, etc. Composition of experiment platform refers to Figure 4.

a）Temperature sensor　　b） Data collection computer

Figure 4 Test Platform

4.3 Test Result

Lay modeling rut trial pieces outdoor and collect temperature of A, B, C, D, E, F, G composed by seven kinds of different materials in different proportion.

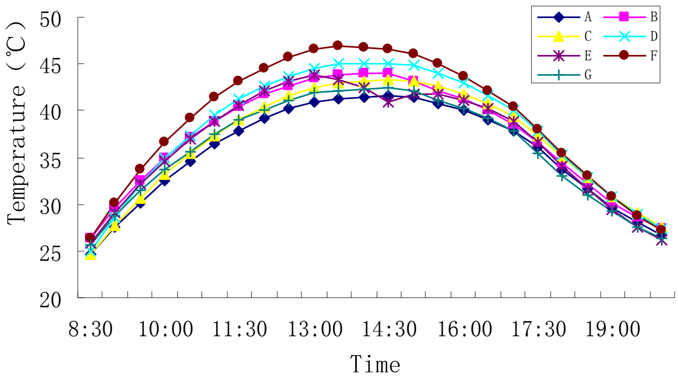

Figure 5 Bottom temperature of different pieces

Summary daily collected outdoor test data into relation figure between bottom temperature of trial pieces and time as shown in Figure 5. We can see that temperature of asphalt rut trial pieces composed by different materials are different, maximum margin is 6℃. Bottom temperature of trial piece made by common material F is the highest, while that of trial piece made by G with good heat insulation performance is lower. As results from above thermal conductivity measuring test show, thermal conductivity of F is greater than that of G, and lower layer temperature of G with good heat insulation performance is lower than that of traditional pavement materials. Therefore, temperature of bottom pavement of materials with smaller thermal conductivity will decrease, thus change inside temperature distribution of pavement structure.

Subtract temperature of upper and lower layer of seven kinds of trial pieces, and quantify insulation performance of all kinds of materials. Establish relation between material temperature margin and time as shown in Figure 6.

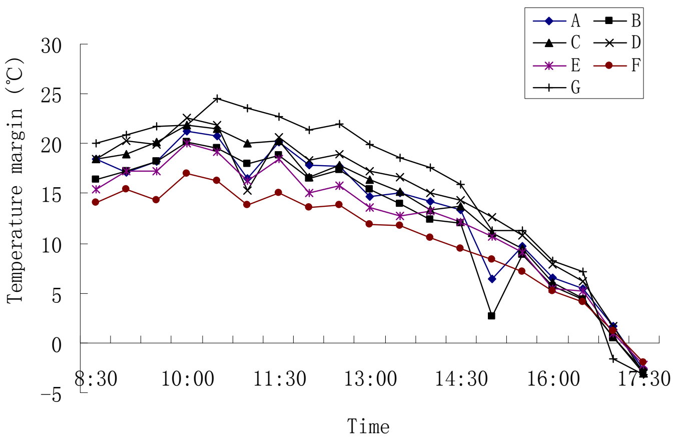

Figure 6 Temperature margin map

As shown in Figure 6, temperature margin of G could reach 25℃ which is the maximum, while that of common material could only reach 16℃ to the maximum. As it is concluded from outdoor test, temperature of outdoor asphalt pavement of asphalt mixture with different thermophysical properties are different and their temperature margins are greater.

5 APPLICATION OF HEAT REFLECTION COATING

From the above analysis, we can see that pavement temperature will be reduced by lower thermal conductivity, therefore, thermal resistance and heat reflection coating which is water-solubility has been used in a entity project.

5.1 Test Road

Choose Hubei section of Beijing-Hongkong-Macao expressway as test road. Beijing-Hongkong-Macao expressway is an important part of expressway network "7918".
Specific location is Xiaogan section in Hubei province of Beijing-Hongkong-Macao expressway, K80+000~K81+000 in Beijing-Hongkong-Macao direction， heat resistance reflection coating 3×60m^2.

5.2 Construction Process

Close transport——coring——bury sensor——close half-width transport and spray——maintain——close another half-width——maintain and open transport——other

Figure 7 Construction site of test road

Figure 8 Test road

5.3 Thermal Insulation Effect

The temperature data of test measured in Oct, 2009 is shown in Table 2:

Table 2 the Comparative temperature of a test day in autumn

Pavement Temperature at Any Time	Normal Pavement (℃)	Using Heat Reflection Coating (℃)	Temperature margin (℃)
12:00	27.7	26	1.7
13:00	28.1	26.4	1.7
14:00	29.5	27.7	1.8
15:00	27.9	26.8	1.1

6 CONCLUSIONS

Above results show that under normal high temperature, pavement temperature distributions of materials with different thermal resistant coefficients are different. This could decrease integral pavement temperature. During outdoor test, bottom temperature margin of common asphalt mixture and asphalt mixture made by smaller thermal conductivity could reach 6℃. Although it is already late autumn, the temperature of pavement which is painted with thermal resistance and heat reflection coating is reduced. In above, this method has great instructive meaning for solving high-temperature rut on asphalt pavement and urban "Heat Island Effect".

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