

Article

Analysis on Environmental Thermal Effect of Functionally Graded Nanocomposite Heat Reflective Coatings for Asphalt Pavement

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Abstract: The heat-reflective coating for asphalt pavement is a functional layer applied on pavement surfaces to reduce heat storage in the pavement via reflecting sunlight, thus inhibiting pavement temperature rise. The objective of this study was to analyze the environmental thermal effect of the self-developed reflective coating, namely, functionally graded nanocomposite reflective coatings, for asphalt pavement. The thermal effects of heat-reflective coatings were compared and analyzed based on field tests. A heating model of the atmosphere layer near the road surface was established. Moreover, the influence of urban road temperature on the thermal comfort of the human body was analyzed. Results showed that the radiation heat of all heat-reflective coatings decreased around two-thirds, and the convective heat decreased nearly 50% when compared with the control asphalt pavement, and the temperatures of the pavement itself and the atmosphere layer were lowered. Additionally, the heat-reflective coating improved the thermal comfort of the human body. This indicated that the heat-reflective coating reduced ambient temperature and relieved the urban heat island effect (UHI) as well as improved the environmental thermal effect.

Keywords: asphalt pavement; functionally graded nanocomposite heat-reflective coating; environmental thermal effect

1. Introduction

Asphalt pavement, with the advantages of high evenness, comfort, and low noise, has been widely applied in road construction. Owing to the black composition materials, its solar thermal radiation absorption rate can be as high as 85% to 95%, and the reflection capability is low, so the asphalt pavement has high thermal absorption characteristics [1]. Especially in a summer season, due to an increase in solar radiation and prolonged daytime, asphalt pavement absorbs a lot of heat and stores it inside, making the surface temperature much higher than the atmosphere temperature. Moreover, with the rapid development of highway construction and acceleration of urbanization in China, a large amount of ground area, especially green space, has been replaced by asphalt pavements, which has exacerbated the urban heat island (UHI) effect [2–5].

Many studies have recently investigated the interaction between asphalt pavements and the surrounding thermal environment. The day radiant heat amount on asphalt pavement is 10.7 times larger than that of grassland [6]. At night, grassland absorbs atmosphere heat instead of radiation, while the amount of heat that asphalt pavement radiates to atmosphere from 18:00 to 6:00 accounts for 1/3 of a day magnitude. In summer, the temperature of asphalt pavement is much higher than that of bare soil during the day, rising above 60 °C in the afternoon; moreover, even before sunrise,

it is 5 °C higher than the atmosphere temperature [7]. According to Stefan–Boltzmann’s law of heat transfer, when the asphalt pavement temperature reaches 63 °C, the long-wave radiation intensity of the pavement is 672 W/m², and the direct radiation intensity of the summer sun is in the range from 700 to 1000 W/m². Because the heat capacity of asphalt concrete is quite high, asphalt pavement acts as the “heating wire” that heats the city, bakes the surrounding atmosphere and living environment, and aggravates the UHI effect of the city [8]. Heat-reflective asphalt pavement can effectively decrease its surface temperature, thereby reducing heat flow to the near-surface atmosphere layer. Mu et al. calculated atmosphere temperature variation according to environmental factors, based on a general model for climate calculation and an assumption that the two heat-reflective coating pavements were used in the 23rd Tokyo district. The results showed that the atmosphere temperature could be lowered by 0.77 °C in the central section; and when the greening area was increased from 23% to 40%, the temperature could be lowered by 0.64 °C [9]. The heat-reflective asphalt pavement cannot only effectively dampen the surface temperature increase and prevent diseases caused by the high-temperature destruction of asphalt pavement but also effectively alleviate the UHI effect caused by asphalt pavement heat radiation [10–14].

The former studies of asphalt pavement impact on the near-surface atmosphere temperature rarely took into account the dependence of reflectance characteristics of asphalt pavement on the solar spectrum. In addition, few functionally graded nanocomposite coatings were studied. Additionally, the path of solar thermal reflection has seldom been analyzed so far. Therefore, the improvement effect of heat-reflective asphalt pavement on environment cannot be accurately evaluated. In this paper, the influence of asphalt pavement on the thermal effect was analyzed using the Stefan–Boltzmann equation, considering measured air and surface temperatures and other factors; the air layer heating model was developed to analyze the temperature of the air layer near the road surface and its changes; finally, human body thermal comfort affected by asphalt pavement at high temperatures was discussed. The above analysis shows that the heat-reflective asphalt pavement has evident effects on the environment.

2. Materials and Methods

Ten reflective coatings for cooling asphalt pavements were developed by our team in our previous study [15]. The coatings studied below were selected from the above coatings. The three coatings applied were quantitatively analyzed for pavement thermal effects on the urban thermal environment by measuring parameters such as the pavement’s temperature and reflectivity, and atmosphere temperature at different times [16–18].

2.1. Materials

The reflective coatings applied were self-devised and included a white coating, pink coating, and gray coating. The paintings used have been patented (Patent no.: CN201010617021.X). They were composed of resin system, functional materials, pigments, dispersant, antisetling agent, and initiating agent, as listed in Table 1. Chemical groups such as C–O–C, –C=O or –OH in the resin should be as few as possible to reduce the sensitivity to ultraviolet (UV). In this study, a modified bisphenol-A epoxy resin was used as the binder, and its light transmittance was above 80%. The parameters of the resin are listed in Table 2. The modified resin has low viscosity and is beneficial to spraying construction. Nanotitanium dioxide was used as the main reflective material. The insulation material and radiation material were floating beads and mica, respectively. The foregoing three materials constituted the functional materials. In other words, the coatings were functionally graded nanocomposite materials. Firstly, the coating could reflect visible light and near-infrared light by nanotitanium dioxide; secondly, the mica could radiate the absorbed heat externally in the form of a long wave; lastly, the floating beads could insulate the heat from entering the interior of the pavement. Via the functionally graded effects to the light and heat, the coatings could reduce the heat of the asphalt pavement from the sunlight. Meanwhile, nanotitanium dioxide and mica have a good shielding function against UV

light. Thus, they provide some protection against UV radiation. The work principle of the coatings is shown in Figure 1 [5]. The reflectivity of each coating was tested by a UV-3600 ultraviolet-visible spectrophotometer (UVS) produced by SHIMADZU (Kyoto, Japan). The reflectivity of these three coats is listed in Table 3. The skid resistant particles composed of 1.18 mm machine-made sand were added on the coatings to improve antiskid performance [15]. An infrared thermometer was used to collect the temperature data. It was manufactured by the BENETECH® (Shenzhen, China), and its model was GM300.

Table 1. The main raw materials of the paintings.

Materials	Main Ingredients
The resin system	Modified liquid bisphenol-A epoxy resin X
Functional materials	Reflective material: Nanotitanium dioxide Insulation material: Floating beads Radiation material: Mica
Pigments	Organic green, organic black, inorganic red, inorganic black
Dispersant	Polyethylene glycol
Antisettling agent	Polyamide wax
Initiating agent	2,2'-Azobis(2-methylpropionitrile)

Table 2. Parameters of the resin.

Resin Type	Epoxy Resin
Appearance	Colorless or light yellow, transparent liquid
Color (Gardiner method)	<2
Density (g/mL, 25 °C)	1.10–1.12
Viscosity (25 °C, mPa·s)	9000–13000
Epoxide equivalent (g/ep)	184–194

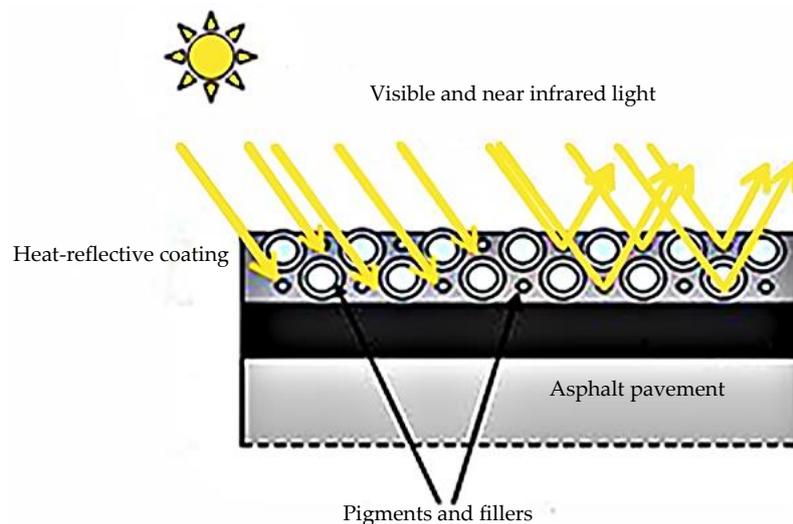


Figure 1. Work principle of the solar reflective coating.

Table 3. Reflectivity of the coatings.

Colors	Reflectivity
White	0.7
Pink	0.5
Gray	0.4

2.2. Temperature Measurement

The field experiments were conducted on HuanShan Road in Xi'an, China. The coatings should be painted twice. After the lower layer was painted and hardened, the upper layer was painted. The painting doses and areas were 400 g/m^2 and 10 m^2 , respectively [15]. In addition, skid resistant particles, 1.18 mm machine-made sand, were added in the middle of two coats, with spreading 160 g/m^2 on the upper layer, forming a “sandwich” structure. The coatings applied are displayed in Figure 2. An infrared thermometer was used to collect the temperature data, as shown in Figures 3 and 4. The infrared thermometer applied is a noncontact infrared thermometer. It was manufactured by BENETECH®, and the model was GM300. Its measuring range is $-32\sim 350 \text{ }^\circ\text{C}$ and its accuracy $\pm 1.5 \text{ }^\circ\text{C}$. The control pavement temperatures were measured from 0:00 to 24:00 every 2 h on 28 July 2012, and the different coating temperatures were measured from 11:00 to 18:00 every 1 h in the day. The measuring points should be in the middle of the painting area in order to reduce the influence of the surrounding environment. The atmosphere temperatures were adopted using the data measured by the China Meteorological Administration in the day.

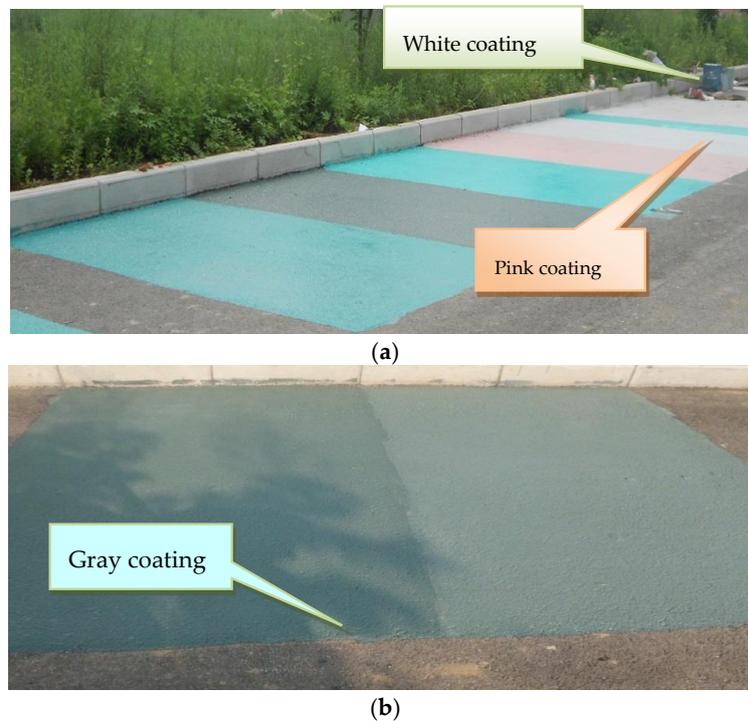


Figure 2. Heat-reflective coatings for asphalt pavement applied in this study included the white and pink coatings shown in (a), and gray coating shown in (b).



Figure 3. Temperature measurement for the control pavement.



Figure 4. Temperature measurement for the coating.

2.3. Analysis on Environmental Heat Effect

Asphalt pavement is affected by various natural factors, such as solar radiation, atmospheric and ground temperatures, precipitation, and wind speed within the natural environment. These heat exchange factors of a road surface form the light and heat environment of asphalt pavement. Figure 5 demonstrates the typical light–heat environment of asphalt pavement. The pavement surface commonly receives direct solar radiation, scattered radiation, and atmosphere counter radiation from the sun and reflects a small radiation outward. Meanwhile, it conducts convective heat exchange with near surface atmosphere and heat transfer with other road layers. Generally, heat transmits between pavement and ambient through conduction, radiation, and convection.

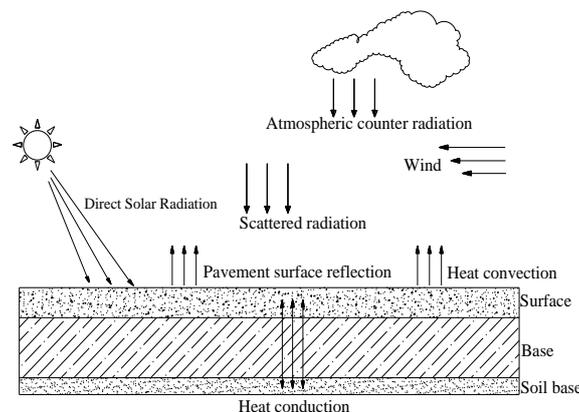


Figure 5. Typical light–heat environment of asphalt pavement.

The atmospheric surface layer is mostly affected by the underlying surface, and its main height range is considered to be up to 100 m above the ground. Figure 6 presents the heat balance between the upper atmosphere and the atmospheric surface layer and the pavement. Under the various heat transfer effects, the atmospheric surface layer can reach the equilibrium temperature instantaneously at a certain temperature.

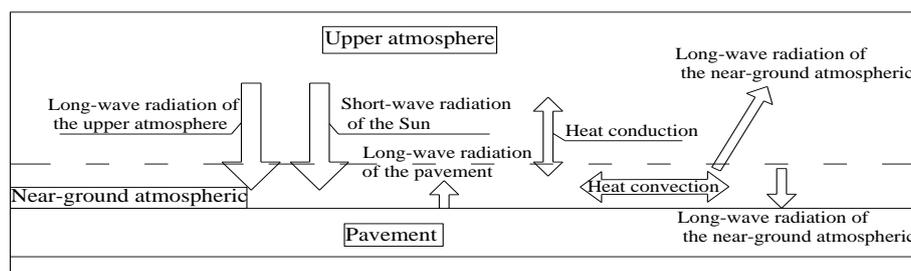


Figure 6. Heat balance of atmospheric surface layer.

Asphalt pavement can absorb as much as 95% of solar radiation because of the lesser reflectivity, resulting in its temperature being much higher than the surrounding temperature. The long-wave radiation of the pavement is proportional to temperature to the fourth power, so that the pavement will generate a large thermal effect to the outside through long-wave radiation, and then adversely affect the external thermal environment. In addition to the long-wave radiation, the pavement transfers heat to the atmosphere by convection. Heat is transferred by convection ceaselessly between the pavement and the flowing atmosphere on the surface of the pavement. The heat convection can be divided into free convection and forced convection. In these two ways, the convection coefficient at the interface changes continuously with the change of the external environment (such as wind speed), but it is generally treated as a constant.

The net heat flux obtained by the object in the natural environment is expressed as Equation (1):

$$q'' = E_s + E_{sky} + E_{sur} + E_h + E_c - E_r \quad (1)$$

where q'' denotes the net heat flux on the surface of the object (W/m^2); E_s is solar energy absorbed (W/m^2); E_{sky} is the atmospheric radiant heat; E_{sur} is the ground radiation heat (W/m^2); E_h denotes the convective heat; E_c is conduction heat (W/m^2); and E_r is radiation scattering loss from the surface of the object. According to Equation (1) and Figure 6, the net heat flux of the near the ground atmosphere can be presented as Equation (2).

$$q_a'' = E_s + E_{sur} + E_h - E_r \quad (2)$$

In Equation (2), q_a'' denotes the net heat flux of atmospheric surface layer (W/m^2); E_{sur} denotes the radiation heat of the asphalt pavement; E_h denotes the convective heat; and E_r denotes the radiation heat of atmospheric surface layer to the outside. In this study, the atmospheric surface layer is considered as a whole, and E_s and E_r could be regarded as invariants, then E_{sur} and E_h are mainly analyzed.

2.3.1. Calculation of the Radiant Heat Effect of the Pavement

Asphalt pavement absorbs solar radiation and atmosphere long-wave radiation, while it radiates heat to the ambient. It has a strong ability to absorb short-waves, the major band of solar radiation, resulting in a rapid rise in its temperature. Its high temperature provides large heat radiation outward, leading to the atmosphere temperature rise, which aggravates the UHI effect. In this section, the heat radiated from the road surface and the long-wave radiation heat from the atmosphere were determined to calculate the heat output from the pavement to the ambient.

- The heat radiated from the pavement to the ambient.

A pavement radiates heat to the ambient environment through two sources, including its own infrared radiation, and the part of the atmosphere long-wave radiation reflected by the ground. The radiation U of the pavement was calculated by the Stefan–Boltzmann equation expressed in Equation (3) [19]:

$$U = \varepsilon_u \times C_s \times [(T_s + 273)/100]^4 \quad (3)$$

where C_s denotes the Stefan–Boltzmann constant as $5.775 (W/(m^2 \cdot K^4))$, ε_u denotes the emissivity, and T_s denotes the road surface temperature ($^{\circ}C$).

- Atmosphere long-wave radiation.

The atmosphere long-wave radiation G_a was calculated by Equations (4) and (5):

$$G_a = 0.820C_s[(T_a + 273)/100]^4 \quad (4)$$

$$G_a = 0.940C_s[(T_a + 273)/100]^4 \quad (5)$$

where G_a denotes the atmosphere long-wave radiation and T_a denotes the measured atmosphere temperature ($^{\circ}\text{C}$). When it was cloud-free, G_a was calculated by Equation (4), while if clouds covered the sky, G_a was calculated by Equation (5).

- Atmosphere long-wave radiation reflected by the road surface.

This radiation part defined as R_a is expressed in Equation (6):

$$R_a = (1 - \varepsilon_u) \times C_s \times \varepsilon_a \times (T_a + 273)^4 \quad (6)$$

where R_a denotes the atmosphere long-wave radiation reflected by the pavement surface (W/m^2) and ε_a denotes the atmosphere radiation coefficient.

Since the direction of this radiation part is upward, it was accounted into the upward radiation of the pavement. Then, the actual upward radiation of the road surface is expressed as Equation (7):

$$R_s = U + R_a = \varepsilon_u \times C_s \times \left(\frac{T_s + 273}{100}\right)^4 + (1 - \varepsilon_u) \times C_s \times \varepsilon_a \times \left(\frac{T_s + 273}{100}\right)^4 \quad (7)$$

- Effective radiation of the road surface.

The road surface radiates heat outward, while it absorbs atmosphere long-wave radiation. Therefore, radiation heat from the road surface to atmosphere should be the radiation heat of pavement minus the long-wave radiation heat of atmosphere and plus the part of atmosphere long-wave radiation reflected by the road surface. When it is cloud-free, the radiant heat effect of the asphalt pavement on the ambient environment is expressed by Equation (8).

$$R_n = U + R_a - G_a = C_s \left(\frac{T_s + 273}{100}\right)^4 [\varepsilon_a + \varepsilon_u(1 - \varepsilon_a)] - 0.82C_s \left(\frac{T_a + 273}{100}\right)^4 \quad (8)$$

As shown in Equation (8), temperatures of atmosphere and of the road surface are the key factors influencing the heat radiation effect of asphalt pavement. Thus, it is necessary to determine their temperatures at each moment to calculate the heat radiation effect of an asphalt pavement within a period of time. The measured temperature represents the temperature at some certain moment. There are two methods to approximate the temperature runs. One method is the calculation of the radiation heat effect using the theoretical formula of asphalt pavement temperature varying with time and then operating the integral with time. The other method is estimation or measurement of the temperatures of the atmosphere and asphalt pavement each hour. Subsequently, their temperatures are fitted to equations. Afterwards, the former fitting equations are substituted into Equation (8), obtaining Equation (9). Lastly, the time integral is conducted. In this paper, we adopted the second method.

$$Q = \int_{t1}^{t2} C_s \left(\frac{T_s + 273}{100}\right)^4 [\varepsilon_a + \varepsilon_u(1 - \varepsilon_a)] dt - 0.82 \int_{t1}^{t2} C_s \left(\frac{T_a + 273}{100}\right)^4 dt \quad (9)$$

2.3.2. Calculation of the Heat Convection Effect of the Pavement

In addition to the radiation heat, asphalt pavement continuously loses heat by pavement-to-atmosphere convection. The temperatures of the road surface and the air and their convective heat transfer coefficient should be determined to calculate the amount of the heat convection. While the coefficient of their interfaces varies with the external factors, it was simplified in this study to be a constant to quantitatively analyze the amount of convective heat. The coefficient was calculated using Equation (10):

$$h = 2.6 \left(\sqrt[4]{\Delta T} + 1.54v \right) \quad (10)$$

where h denotes the convective heat transfer coefficient ($\text{W}/\text{m}^2\cdot^\circ\text{C}$), ΔT denotes the temperature difference at the heat convective interface ($^\circ\text{C}$), and v denotes the wind speed (m/s). The wind speed was assumed to be a constant ($1 \text{ m}/\text{s}$) in this paper. The amount of the heat convection per unit area over a certain period was calculated by integration using Equation (11).

$$Q = \int_{t_1}^{t_2} 2.6(\sqrt[4]{T_s - T_a} + 1.54) \times (T_s - T_a) dt \quad (11)$$

As shown in Equation (11), in any period of time, t_1 denotes the initial time and t_2 denotes the ending time. The time-dependent equations of the atmosphere temperature and pavement temperature could be substituted into Equation (11) to calculate the heat convection amount at any period of time. The result could present the energy exchanged by heat convection between asphalt pavement and the atmosphere per square meter in a certain period of time.

2.3.3. Analysis of the Thermal Environment of the Atmosphere Layer Near Pavement

As shown in Figure 7, the atmosphere surface layer near pavement, separated from the atmosphere, was considered as the object in this study based on the analysis of the heated environment. The long-wave radiation of the asphalt pavement was taken as the sole heat source. Then, a model was established to simulate the temperature distribution, considering a long-wave radiation from the atmosphere layer, and the convection heat transferred through the atmosphere layer, the pavement, and the upper atmosphere layer. The atmosphere surrounds the earth and its boundary is currently considered at 1.5 km high above the ground surface. The atmosphere surface layer is mostly affected by the underlying surface, and its main height range is considered up to 100 m above ground. Therefore, the upper boundary of the model proposed was defined as 100 m above the road surface, while the lower boundary was the asphalt pavement surface.

A two-dimensional atmospheric layer model was designed to simulate heat flow in this study. A cross-section in a driving direction was represented as a geometric model. The x -axis of the model was perpendicular to the driving path, and its positive direction was right-side. The y -axis was perpendicular to the road surface; it had a positive direction upward. The sketch of the geometric model is shown in Figure 7, where R is the long-wave radiation of the atmospheric surface layer and V is long-wave radiation of the pavement.

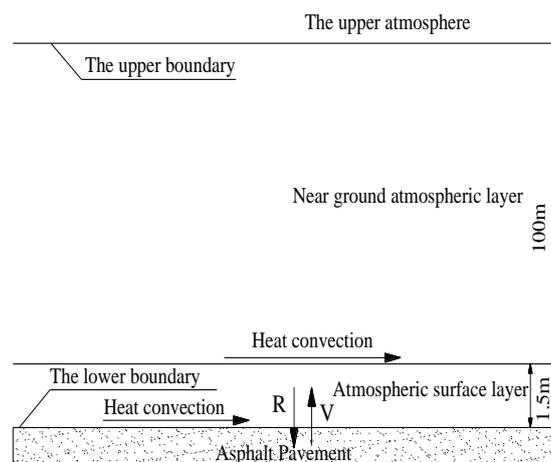


Figure 7. The sketch of the simulation of the atmospheric layer.

Table 4 lists the atmosphere parameters of the model. Ansys (V18.0), a finite element software, was used to simulate the atmosphere heating process by control asphalt pavement and the heat-reflective asphalt pavement, and the heating process at the measured temperature [20]. Via the analysis of the

heating process, the atmosphere temperature and its variation of this layer were studied in this paper. The atmosphere heating processes by the asphalt pavement and by the heat-reflective pavement were simulated using the finite element software, taking into account the above conditions. The temperature variations of the atmosphere layer near the road surface were studied by the above simulation.

Table 4. Atmosphere parameters of the model.

Parameters	Value	Unit
Density	1.29	kg/m ³
Heat conductivity	0.0265	W/m·k
Specific heat capacity	0.24	kcal/kg·°C
Convective heat transfer coefficient (between road surface and atmosphere)	18	W/m ² ·k
Convection heat transfer coefficient (flow atmosphere between layers)	20	W/m ² ·k

2.3.4. The Influence of Urban Road on Human Thermal Comfort

An outdoor thermal environment has a direct impact on humans' comfort. At a certain ambient temperature, the human body heat increases with the increase of the ambient temperature, while the body regulates temperature via sweating to maintain the thermal balance. If an ambient temperature is too high, beyond the range that can be adjusted by the body's regulating system, body temperature may rise up, causing human physiological disease and danger.

The influencing factors on human thermal comfort (HTC) mainly include temperature, wind speed, relative air humidity and solar radiation.

Temperature is the most important factor influencing HTC, including atmosphere temperature and average radiant temperature. The existence of urban roads will cause the atmosphere temperature around the road to be higher than the ambient temperature, making HTC near the road lower than other areas, while the application of the functionally graded nanocomposite heat-reflective coatings can greatly reduce the temperature, thus improving HTC.

Wind speed has an important impact on HTC. Different types of urban underlying surfaces can change wind speed and direction, affecting the convective heat loss of the human body, thus having a greater impact on the HTC. HTC increases with the increase in wind speed. This is because the wind is good for the body to sweat and cool down, but as the temperature increases, the effect of wind speed on HTC will gradually decrease.

Humidity also has an effect on HTC. Sudden change in humidity can alter HTC, and humans will feel stuffy or cool. In reality, humidity rarely changes abruptly; therefore, the influence of humidity on HTC can be ignored during a period of time.

Solar radiation can also have a significant influence on HTC. The radiation wavelength of the human body is in the range of 2.5 to 15 μm, and the peak wavelength is about 9.3 μm. The radiation in the 8–14 μm band accounts for 46% of the total radiation of the human body. At the same time, the human body is a good infrared absorber, and the wavelength of absorption to solar radiation is mainly 8–14 μm. The functionally graded nanocomposite heat-reflective coatings could reduce solar radiation to the pavement, thus indirectly improving HTC.

Considering the combined effect of the above factors, the outdoor thermal comfortable degree (OTCD) was adopted to analyze the influence of urban roads on HTC in this study. Related studies have proposed some relationships between OTCD and influencing factors [21]. OTCD could be expressed as Equation (12) (wind speed > 1 m/s) [22]:

$$OTCD = [T_g + 1.45(RH - 0.3) - 0.075(T_a - 25)] [1 + 0.00065(T_a - 25)] v^{0.227} + 26.76 - 26.79v^{0.249} + (0.6 - 0.08v^{1.496})(T_a - 25)/5 - (0.1v^{1.048} - 0.4)(RH - 0.3)/0.7 + (1.93RH^{1.97} - 0.5)(T_a - 25)/15 \quad (12)$$

where T_g denotes the effective temperature of the human body under the combined effect of radiant and convection heat in a radiant thermal environment. T_g represents the temperature felt by the human body. RH denotes the relative atmosphere humidity and v denotes the wind speed. The influence of

temperature on OTCD was analyzed in this paper. For the sake of simplicity, other parameters were assumed to be a constant, namely, T_g was taken as 35 °C, RH was taken as 50%, and v was taken as 1.5 m/s. As a result, Equation (12) could be approximately simplified to Equation (13). A person felt comfortable when OTCD was 34.9–35.3, hot when OTCD was 35.3–35.7, and very hot when OTCD was more than 35.7 [23].

$$\text{OTCD} = 0.0447t + 34.154 \quad (R^2 = 0.9982) \quad (13)$$

3. Results and Discussion

3.1. Results of the Temperatures Measurement Tests

Table 5 presents the measured temperatures of atmosphere and road surface. While, temperatures of pavements with different coatings are listed in Table 6.

Table 5. Measured temperatures of atmosphere and road surface (°C).

Time (h)	Atmosphere Temperature (°C)	Road Surface Temperature (°C)
0	30	39.1
2	30	37.4
4	28	36.3
6	29	37
8	30	44
10	32	48.2
12	35	54
14	37	56.9
16	38	59.4
18	36	56.9
20	34	51.2
22	30	42.1
24	30	38.5

Table 6. Measured temperature of pavement surface with different coating (°C).

Time (h)	11	12	13	14	15	16	17	18
Atmosphere temperature	33	35	36	37	37	38	37	36
Control asphalt pavement	48.4	54	58.2	59.4	63.3	56.9	52.5	51.2
White coating	37	46.7	47.2	50.1	51.9	55.7	44.1	43.8
Pink coating	38.6	45	47.2	48.2	51.2	47.3	43.7	44
Gray coating	42.4	49.2	52	56	57.3	56.7	55.7	53.6

When radiation is projected onto an object, a part of it is absorbed by the object, a part of it is reflected, and the rest is transmitted through the object, as shown in Figure 8. Assuming that the total radiation energy projected on the object is E_λ , the absorbed is E_α , the reflected is E_β , and the transmitted is E_τ . Subsequently, Equation (14) was obtained based on the principle of energy conservation.

$$E_\lambda = E_\alpha + E_\beta + E_\tau \quad (14)$$

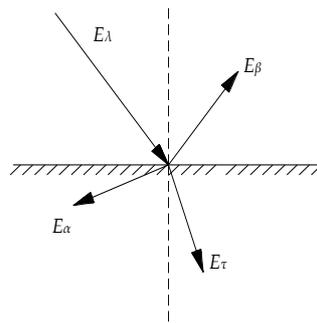


Figure 8. The absorption, reflection, and transmission of heat radiation from pavement.

Equation (15) was obtained by dividing E_λ in both sides of Equation (14):

$$\alpha + \beta + \tau = 1 \tag{15}$$

where $\alpha = \frac{E_\alpha}{E_\lambda}$ denotes absorbance; $\beta = \frac{E_\beta}{E_\lambda}$ denotes reflectivity; and $\tau = \frac{E_\tau}{E_\lambda}$ denotes transmittance. Radiation for asphalt pavement cannot be transmitted backward, thus $\tau = 0$, so Equation (15) can be simplified to Equation (16). The asphalt pavement was assumed to be the diffuse-gray surface; therefore, the emissivity was set to be equal to the absorbance in this paper.

$$\alpha + \beta = 1 \tag{16}$$

Based on the above analysis and Table 3, ϵ_u was taken as 0.3 for white coating, 0.5 for pink coating, and 0.6 for gray coating, respectively.

3.2. Analysis of Environmental Thermal Effect

3.2.1. Radiant Heat Effect

The measured temperatures of each coating and atmosphere temperatures are shown in Figures 9 and 10, respectively. As shown in Figure 9, the curves are plotted by fitting the measured temperatures of each coating using a fifth-order polynomial in the period from 11:00 to 18:00. Figure 10 presents the atmosphere temperature curve in the period from 11:00 to 18:00. The curve is also fitted using a fifth-order polynomial.

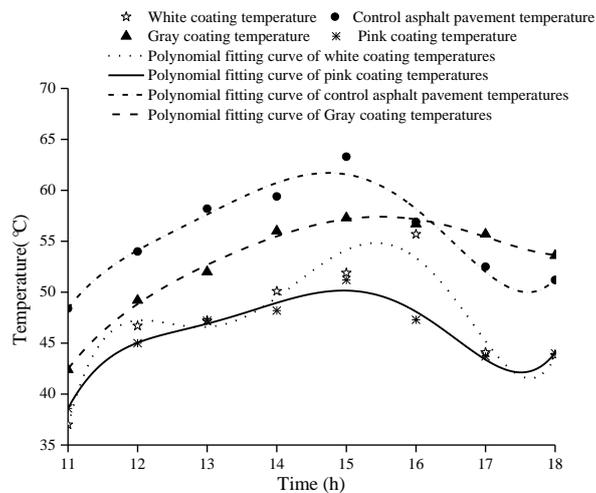


Figure 9. Surface temperature of different coating pavement.

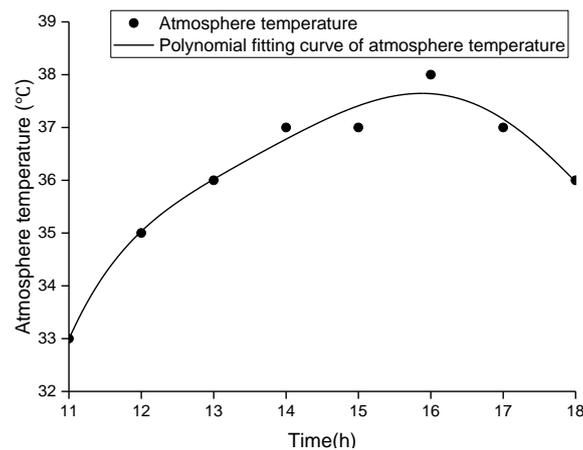


Figure 10. Atmosphere temperatures.

According to the fitting curve in Figures 9 and 10, the temperature fitting formulas of the control asphalt pavement, white coating, pink coating, and gray coating were expressed as Equations (17)–(20), respectively:

$$T_{as} = 0.029t^5 - 2.0351t^4 + 56.651t^3 - 783.15t^2 + 5385.4t - 14708 \quad (R^2 = 0.9576) \quad (17)$$

$$T_w = 0.0894t^5 - 6.4861t^4 + 186.82t^3 - 2670.6t^2 + 18953t - 53389 \quad (R^2 = 0.9442) \quad (18)$$

$$T_p = 0.0367t^5 - 2.6241t^4 + 74.61t^3 - 1054.2t^2 + 7408.8t - 20687 \quad (R^2 = 0.9749) \quad (19)$$

$$T_{gr} = 0.0091t^5 - 0.6558t^4 + 18.846t^3 - 269.72t^2 + 1929.1t - 5484.6 \quad (R^2 = 0.9934) \quad (20)$$

where T_{as} denotes the measured temperature of control asphalt pavement, T_w denotes the measured temperature of the white coating pavement, T_p denotes the measured temperature of the pink coating pavement, T_{gr} denotes the measured temperature of the gray coating pavement, and t denotes the time.

The temperature fitting formula of atmosphere temperature is expressed as Equation (21). Equations from (17) to (20) were substituted into Equation (9), and then the radiation heat effect of the control asphalt pavement was calculated from 11:00 to 18:00. An ε_u value of 0.92 was adopted for the asphalt pavement in this paper [23], and ε_a was chosen as 0.74 [24]. Additionally, the radiation heat effects of the white coating, pink coating, and gray coating were calculated by the above method. The results are shown in Figure 11.

$$T_a = 0.002t^5 - 0.217t^4 + 6.506t^3 - 96.48t^2 + 711.7t - 2059 \quad (R^2 = 0.9223) \quad (21)$$

It can be seen in Figure 11 that all the heat is positive, which indicates continuous heat transfer from the asphalt pavements to the ambient environment through the radiation heat effect. Three heat-reflective coatings reduced the amount of radiated heat by nearly two-thirds in comparison to the control asphalt pavement, and the gray coating reduced that by half. As the coatings were painted in part of the road, the surface of the asphalt pavement was not completely covered. Therefore, the radiation heat could be relatively larger, which influenced by the heat flow of the surrounding road. If the asphalt pavement were totally covered, the radiation heat of the heat-reflective coating could be further reduced.

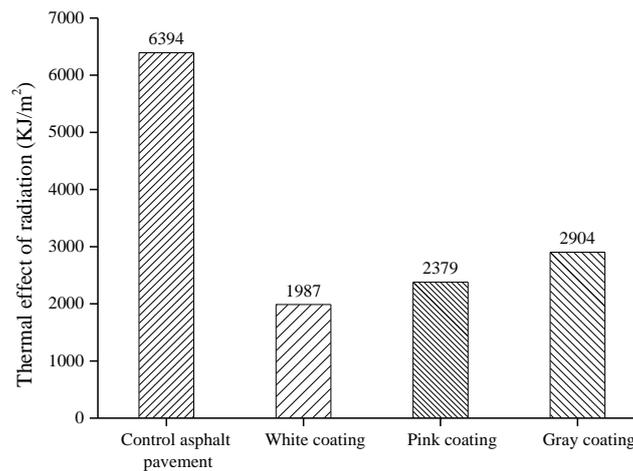


Figure 11. Radiation effect of different asphalt pavement.

The above analysis demonstrates that the asphalt pavement radiates much heat to the ambient environment, and the heat-reflective coating reduces the radiation absorption rate and the temperature of the pavement and reduces the heat radiated outward. Therefore, the heat-reflective coating helps to reduce the temperature of the ambient environment and the UHI effect.

3.2.2. Convective Heat Transfer Effect

The temperature difference between the pavement and atmosphere determines their convective heat transfer coefficient and the amount. Therefore, the pavement temperatures directly determine its convective heat transfer effect. The convection heat transfer between each square meter of the pavement and atmosphere was calculated by Equation (8), where v was taken as 1 m/s. Figure 12 shows the results of the heat convection effect.

Figure 12 displays that the convective heat transfer of the heat-reflective coating is significantly reduced compared with the control asphalt pavement. Because convective heat transfer is only related to the temperature of the pavement and atmosphere, the temperature of the pink coating is lower than that of the white and gray coatings, so its convective heat transfer amount is less than that of the latter two coatings. As the temperature rises, the thermal effect of the convection heat transfer of the control asphalt surface increases continuously. The results indicate that the heat-reflective coating can reduce the heat hazard to the environment.

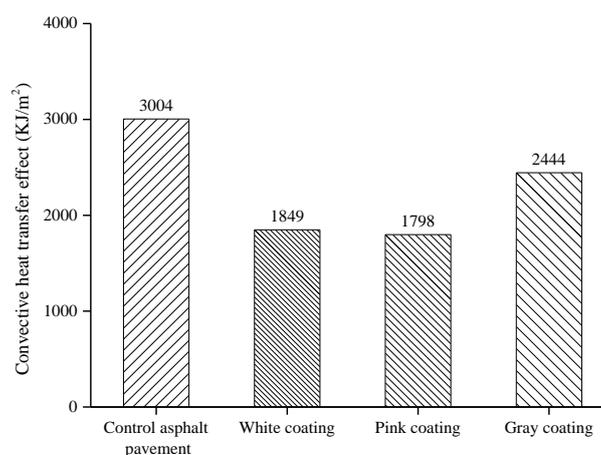


Figure 12. Heat convection effect of different asphalt pavement.

3.2.3. Comparative Analysis of Thermal Effects of Different Underlying Surfaces

The temperature and reflectivity of common underlying surfaces in cities are studied to compare the thermal effects of different underlying surfaces, as shown in Table 7.

Table 7. Common underlying surfaces in cities.

Underlying Surface	Fitted Temperature Curve	ϵ_u
Grass	$T_g = 30.52 + 1.98 \sin[\frac{\pi}{10.36}(t - 10.1)]$	0.75 [25]
Square	$T_b = 39.05 + 6.80 \sin[\frac{\pi}{9.96}(t - 9.21)]$	0.70
Concrete	$T_c = 39.98 + 6.14 \sin[\frac{\pi}{9.89}(t - 9.56)]$	0.75 [26]

Figure 13 shows the thermal effect of different underlying surface. In the open soil system represented by Grass, nighttime temperature is lower than daytime temperature. Even if the radiation effect is positive in the daytime, the thermal effect is negative within 24 h. It indicates that the heat absorbed by the grass at night is much higher than the radiant heat during the daytime. Therefore, the greenbelt has a positive effect on mitigating the UHI. In addition, in the closed system represented by asphalt pavement, the thermal effect is positive and the highest. This indicates that the heat is continuously exported to the environment all through the day. The heat from the pavement especially has an adverse effect on UHI in the summer. After applying a solar heat-reflective coating on the road surface, the thermal effect of the pavement is significantly reduced, about only half of that of uncoated pavement. The maximum reduction of heat per square meter is as much as 10,000 KJ, indicating that the coatings are beneficial in lowering the ambient temperature and reducing the hazard of the UHI.

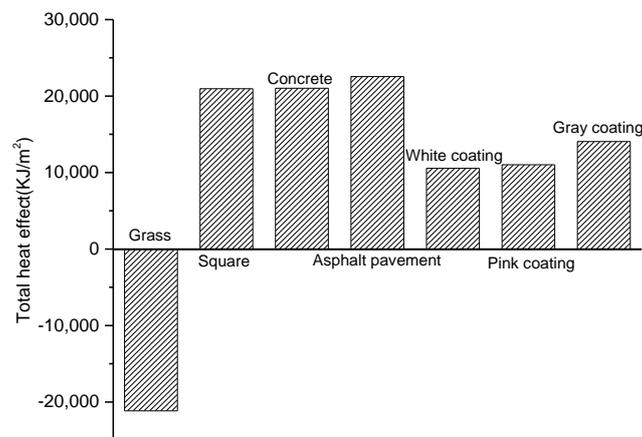


Figure 13. Thermal effect of different underlying surface.

3.3. Analysis of the Pavement Surface–Atmospheric Surface Layer–Thermal Environmental Influence on the Near-Ground Atmosphere

Figure 14 shows the comparison of the atmosphere temperature, the road surface temperature, and the calculated values of the atmospheric surface layer temperature for control asphalt pavement.

As shown in Figure 14, the temperature of the control asphalt pavement is much higher than the atmosphere temperature, and the temperature difference reaches approximately 20 °C. Since the heat conductivity and specific heat capacity of the atmosphere are relatively small, the temperature of the atmospheric surface layer near the road becomes higher than the road itself under the influence of its long-wave radiation. Temperature variations of the atmospheric surface layer and the road surface are different, but the trends are basically the same.

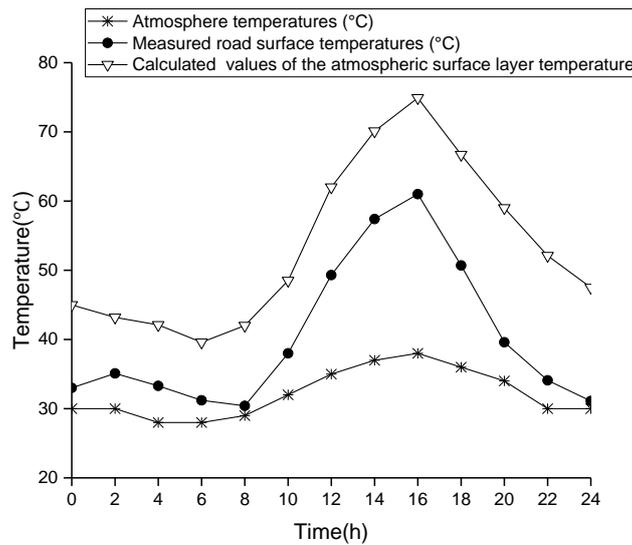


Figure 14. Comparison on atmosphere temperatures, the measured road surface temperatures, and the calculated temperatures of the atmospheric surface layer.

Temperatures at different heights above the road surface are plotted in Figure 15. The temperature of the atmospheric surface layer above the road surface decreases with height increase, and the trend is relatively flat, varying greatly only at 15 and 30 cm above the surface. When the height reaches 1.5 m, the maximum temperature almost equals the atmosphere temperature.

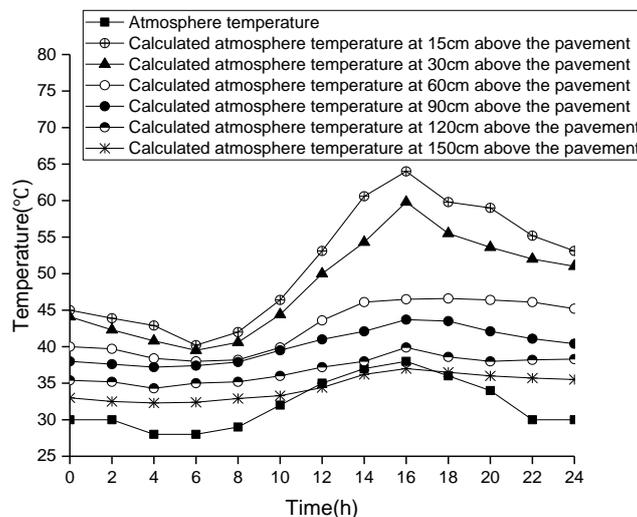


Figure 15. Diurnal variation of temperature at different heights from the road surface.

From Figure 15, due to the presence of the asphalt pavement, the temperature near the surface of the road is much higher than the temperature of the surrounding atmosphere, so pedestrians walk on the asphalt and feel baked in the summer. Additionally, this baking feeling is considered more serious in the absence of wind. Under this condition, less heat is transferred by natural convection and heat conduction, which makes the surface forming a hot “microclimate”, affecting the comfort of pedestrians.

The heating model simulated the temperature of the atmospheric surface layer in order to analyze its heating process by the heat-reflective coatings. No separate layer structure was designed for the heat-reflective coating, only considering increasing the reflectivity of the pavement and reducing the heat absorption rate. The results are plotted in Figure 16.

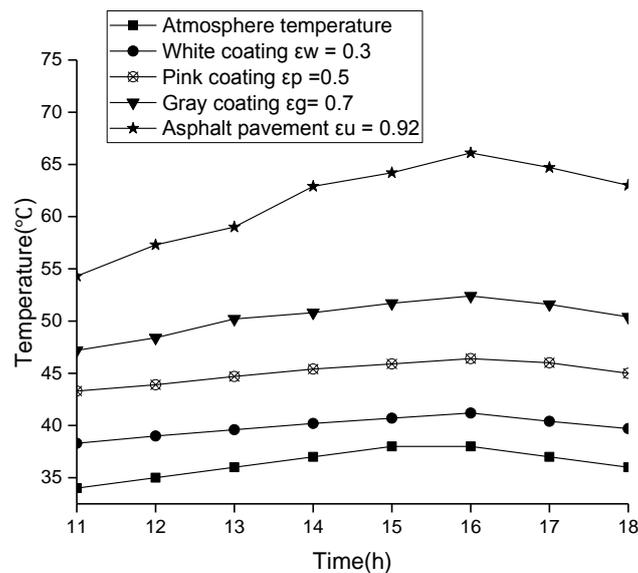


Figure 16. Temperature curves of different coating pavements.

As shown in Figure 16, as the reflectivity of the coating increases, the atmospheric surface layer temperature gradually decreases. This is maybe the reduction of absorbed solar and atmosphere long-wave radiation because of an increase in reflectivity. Thus, the heat source of the atmospheric surface layer, an asphalt pavement, correspondingly reduces its temperature. The average temperature of the white coating was 40 °C, that of the pink coating about 45 °C, and that of the gray coating exceeded 50 °C. The temperature of the atmospheric surface layer above the heat-reflective coating was significantly lower than that of the control asphalt pavement; the maximum decrease was about 25 °C and the minimum was more than 10 °C. The results indicate that the heat-reflective coating improves the heat reflectivity of the pavement and effectively reduces the temperature of the pavement and the temperature of the atmospheric surface layer.

3.4. Analysis of OTCD

OTCD of the heat-reflective coating and of the control asphalt pavement were calculated by Equation (13). The results are plotted in Figure 17.

At higher temperatures, the body feels hotter. Meanwhile, high temperature of the atmospheric surface layer will intensify an increase of the OTCD, which reached a maximum of 37.5. Therefore, humans feel unbearably hot. As can be seen in Figure 17, the three coatings raise the OTCD of the surface atmosphere by less than 1. Although the heat-reflective coating was still very hot, the maximum OTCD was reduced by 1.5 compared to that of the control asphalt pavement. The atmosphere temperature generally depends on the city's climate. However, for a certain area in the city, its microclimate may be affected by factors such as the type, material, greening, and artificial heat release of the underlying surface. Therefore, the temperature of the microclimate is different from the overall temperature of the city. The urban road makes the atmosphere temperature around the road higher than the ambient temperature, resulting in the thermal comfort near the road lower than other areas, while the heat-reflective coating just relieves this discomfort.

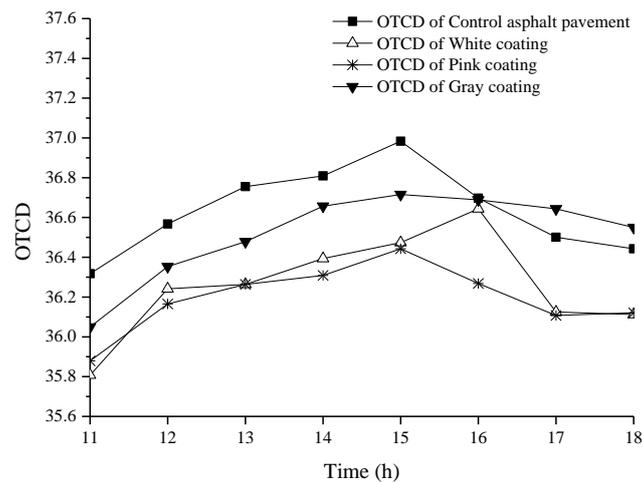


Figure 17. Comparison on outdoor thermal comfortable degree (OTCD) between heat-reflective coatings and control asphalt pavement.

4. Conclusions

- Pavement can transfer heat to the ambient environment by radiation and convection. The temperature of the road surface plays a decisive role in the thermal effect. The radiation heat of all functionally graded nanocomposite heat-reflective coatings decreased by near two-thirds, and the convective heat decreased by near 50% in comparison to the control asphalt pavement. The functionally graded nanocomposite heat-reflective pavement reduced the environmental thermal effect, which was beneficial in relieving the urban heat island effect.
- The heating model was established to simulate asphalt pavement with and without functionally graded nanocomposite heat-reflective coatings to heat the atmosphere surface layer near the pavement. The temperature of the atmosphere surface layer was much higher than the ambient temperature. The functionally graded nanocomposite heat-reflective asphalt pavement reduced the temperature of the pavement itself and the atmosphere surface layer near the pavement.
- Under certain conditions, outdoor thermal comfortable degree (OTCD) increases linearly with the increase of temperature, while human thermal comfort decreases with the increase of temperature and OTCD. The OTCD values of the functionally graded nanocomposite heat-reflective coatings were reduced compared to those of the control asphalt pavement. Therefore, the functionally graded nanocomposite heat-reflective asphalt pavement improves human thermal comfort.

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