

Heat transfer model for microwave hot in-place recycling of asphalt pavements

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Abstract: In order to solve for temperature fields in microwave heating for recycling asphalt mixtures, a two-dimensional heat transfer model for the asphalt mixtures within the heating range is built based on the theory of unsteady heat conduction. Four one-dimensional heat transfer models are established for the asphalt mixtures outside the heating range, which are simplified into four half-infinite solids. The intensity of the radiation electric field is calculated through experiment by using heating water loads. It is suggested that the mathematical model of boundary conditions can be established in two ways, which are theoretical deduction and experimental reverse. The actual temperature field is achieved by fitting temperatures of different positions collected in the heating experiment. The simulant temperature field, which is solved with the Matlab PDE toolbox, is in good agreement with the actual temperature field. The results indicate that the proposed models have high precision and can be directly used to calculate the temperature distribution of asphalt pavements.

Key words: asphalt pavements; microwave hot in-place recycling; heat transfer model; boundary condition; intensity of radiation electric field; microwave heating experiment

Asphalt mixtures have been widely used in constructing high grade highways, bridges and airport pavements. Due to natural environments and heavy traffic loads, various forms of functional damages, such as cracks, rough surfaces, pits and grooves, bleeding, inevitably occur in asphalt pavements. This requires prompt repair and maintenance to restore the normal function of pavements. The hot in-place recycling technique is widely used in pavement maintenance at present. Hereinto, the adoption of microwave heating is a new research direction of the hot in-place recycling technique. During microwave heating, molecules move violently and impact with each other under the action of high frequency alternating electromagnetic fields. Much heat is produced and transformation between electric energy and thermal energy of material is realized. This kind of heating can make internal and external material hot simultaneously and has the virtues of rapid heating, deep penetration, and excellent controllability^[1-2]. Currently, the microwave recycling technology has received much attention.

Foreign scholars and engineering technicians have developed relevant research in the application of microwave heat-

ing to recycle asphalt pavement and have made some achievements. Bosisio is one of the earliest researchers studying hot in-place recycling of asphalt pavement. He applied microwave energy to asphalt road maintenance and discovered that the microwave power at 2 450 MHz can be effectively coupled into an asphalt pavement to a depth of 12 cm without overheating the top layer. Furthermore, a transverse road crack can be sealed by the microwave power and the repaired surface can be exposed to heavy traffic conditions during the whole winter with promising results. Shoenberger et al.^[3] recycled asphalt concrete pavements by microwave heating, which realized that the possibility of recycling increases from 40% to 100%. The effect of microwaves on asphalt cement binders was evaluated using conventional viscosity and penetration tests^[3].

The research above has mainly aimed at experiments of asphalt mixture recycling. Along with the deep research, the heat transfer mechanism of microwave heating has become an urgent problem to be solved. Hopstock^[4] put forward that microwaves can enter pavements perpendicularly without considering the heat of horizontal transfer. He established a one-dimensional thermal equilibrium model and solved it by the finite differential method^[4]. Obviously, the accuracy of the one-dimensional model is hard to be guaranteed in fact. Laurence et al.^[5] studied the temperature rise induced by pulsed microwave exposures by using the principle of heat conservation and assuming a distribution of energy deposited in the tissue medium. Dincov et al.^[6] studied heat and mass transfer mechanisms of multi-phase porous media under intensive microwave heating. They used the finite difference time-domain method and the finite volume method to solve equations that describe the electromagnetic field and heat transfer. The model was able to reflect the evolution of both temperature and moisture fields as well as energy penetration. However, the two models proposed above are complicated to calculate. In addition, they cannot be used to describe the recycling mechanism of asphalt pavements because of the different structures of microwave heating systems. It is very difficult to measure temperature distribution and predict heat transfer laws of asphalt mixtures during a microwave heating experiment technically. Hence, establishing the heat transfer model of microwave hot in-place recycling for asphalt pavements has important theoretical significance and practical value.

1 Heat Transfer Model

1.1 Heat conduction differential equation

Within the microwave heating range, the temperatures of asphalt mixtures continuously rise. The heat transfer process

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is unsteady. On the assumption that thermal conductivity and density do not change with temperature, the heat conduction equation of an arbitrary micro-unit taken from asphalt mixtures is

$$\lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \phi = \rho c \frac{\partial T}{\partial t} \quad (1)$$

where λ is the thermal conductivity of asphalt mixtures; T is the temperature of asphalt mixtures; ϕ is the strength of internal heat source; ρ is the density of asphalt mixtures; c is the specific heat of asphalt mixtures; and t is the heating time.

According to the electromagnetic field propagation law in materials, the strength of microwaves in the asphalt mixtures reduces slowly along the depth^[7]. In addition, the temperature distribution changes little in direction during the heating experiment. So it can be considered that $\frac{\partial^2 T}{\partial z^2}$ is approximately equal to zero. Thus Eq. (1) can be simplified into a two-dimensional partial differential equation:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\phi}{\lambda} = \frac{\rho c}{\lambda} \frac{\partial T}{\partial t} \quad (2)$$

Outside the microwave heating range, asphalt mixtures can be simplified as four semi-infinite solids (see Fig. 1). In order to calculate conveniently, four coordinate systems are built to solve temperature distribution in this range.

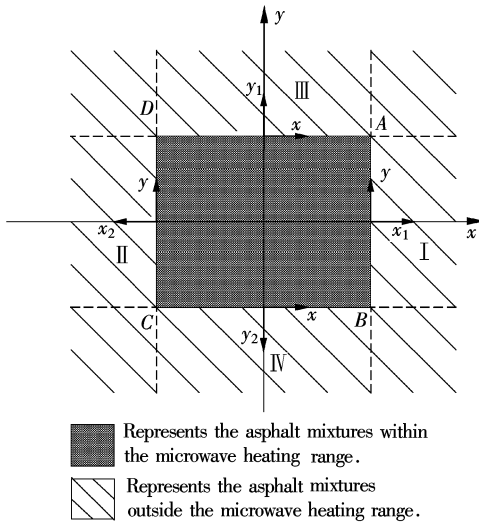


Fig. 1 Microwave heating of asphalt mixtures

The heat transfer equation in a horizontal direction (sections I and II in Fig. 1) is

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c}{\lambda} \frac{\partial T}{\partial t} \quad (3)$$

The coordinate system (x_1, y) is adopted in section I and the coordinate system (x_2, y) is adopted in section II. It is assumed that $\eta_{x_{1,2}} = x_{1,2}/2\sqrt{\alpha t}$, where $\alpha = \lambda/(\rho c)$. From the boundary conditions: $x_{1,2} = 0, \eta_{x_{1,2}} = 0, T = T_{wx_{1,2}}; x_{1,2} = \infty, \eta_{x_{1,2}} = \infty, T = T_0$; the solution of Eq. (3) can be obtained:

$$T = \frac{2(T_0 - T_{wx_{1,2}})}{\sqrt{\pi}} \int_0^{\eta_{x_{1,2}}} e^{-\eta^2} d\eta + T_{wx_{1,2}} \quad (4)$$

where $T_{wx_{1,2}}$ is the temperature at the interface between the middle heating section and sections I, II (AB, CD in Fig. 1); T_0 is the initial temperature of the asphalt mixtures.

The heat transfer equation in a vertical direction (sections III and IV in Fig. 1) is

$$\frac{\partial^2 T}{\partial y^2} = \frac{\rho c}{\lambda} \frac{\partial T}{\partial t} \quad (5)$$

The coordinate system (x, y_1) is adopted in section III and the coordinate system (x, y_2) is adopted in section IV. In the same way, the solution of Eq. (5) can be obtained:

$$T = \frac{2(T_0 - T_{wy_{1,2}})}{\sqrt{\pi}} \int_0^{\eta_{y_{1,2}}} e^{-\eta^2} d\eta + T_{wy_{1,2}} \quad (6)$$

where $\eta_{y_{1,2}} = y_{1,2}/(2\sqrt{\alpha t})$, and $T_{wy_{1,2}}$ is the temperature at the interface between the middle heating section and sections III and IV (BC, AD in Fig. 1).

1.2 Strength of internal heat source

Microwave heating means that the electromagnetic energy of the microwaves is converted into the thermal energy in the materials. Asphalt mixtures absorb energy from the microwave field, which is dissipated in the mixtures in the form of heat. A micro unit, whose volume is $dx dy dz$, is arbitrarily taken from the heating asphalt mixtures. The strength of the internal heat source can be obtained in the unit^[11]:

$$\phi = \frac{1}{2} \omega \epsilon_0 \epsilon''_{\text{eff}} \bar{E}^2 \quad (7)$$

where ω is the angular frequency of the microwaves; ϵ_0 is the dielectric constant of vacuum; ϵ''_{eff} is the relative dielectric loss gene of the asphalt mixtures; and \bar{E} is the average instantaneous value of electric field intensity in the unit.

1.3 Intensity of radiation electric field

The value of \bar{E} must be determined in order to calculate Eq. (7). Given that the radiation electric field distributes uniformly, the average temperature can be calculated by the heat conduction equation. Direct measure of the radiation electric field in asphalt mixtures is very difficult to achieve technically. Therefore, experiments of heating water are adopted to estimate the intensity of the radiation electric field. During the experiment, the microwave energy is converted into the thermal energy of water. The quantity of heat per unit time absorbed by water can be calculated through measuring the temperature rise of water. The output power of a magnetron is obtained by the work-energy principle, and the intensity of the radiation electric field is finally obtained. The calculation process is as follows:

The energy absorbed by the water load is

$$Q_1 = C_1 M_1 \Delta T' \quad (8)$$

The power consumed by the water load is

$$P_1 = \frac{Q_1}{\Delta t} = \frac{C_1 M_1 \Delta T'}{\Delta t} \quad (9)$$

where C_1 is the specific heat of the water; M_1 is the quality of the water; $\Delta T'$ is the temperature rise of the water; and Δt is the heating time.

The actual output power when heating the water is

$$P = \frac{P_1}{1 - |\Gamma_1|^2} \quad (10)$$

The power consumed by asphalt mixtures when heating them is

$$P_2 = P(1 - |\Gamma_2|^2) = \frac{C_1 M_1 \Delta T'}{\Delta t} \frac{1 - |\Gamma_2|^2}{1 - |\Gamma_1|^2} \quad (11)$$

where Γ_1 is the reflection coefficient of microwaves in the water load, and Γ_2 is the reflection coefficient of microwaves in the asphalt mixtures.

Thus on the basis of the relationship between P_2 and \bar{E} , the intensity of the radiation electric field can be solved by Eq. (11).

$$\bar{E} = \sqrt{\frac{C_1 M_1 \eta \Delta T' (1 - |\Gamma_2|^2)}{A \Delta t (1 - |\Gamma_1|^2)}} \quad (12)$$

where A is the area of the heated asphalt mixtures, and η is the wave drag of the asphalt mixtures. η can be determined by

$$\eta = \sqrt{\frac{\mu_0 \mu_r}{\varepsilon_0 \varepsilon'}} \quad (13)$$

where μ_0 is the permeability of the vacuum, μ_r is the relative permeability of the asphalt mixtures, and ε' is the relative dielectric constant of the asphalt mixtures.

The radiation electric field distributes uniformly with the assumption that the heater structure is optimal. From Eqs. (2), (7) and (12), the heat conduction equation within the microwave heating range can be transformed as

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\omega \varepsilon_0 \varepsilon''_{\text{eff}} C_1 M_1 \eta \Delta T' (1 - |\Gamma_2|^2)}{2 A \Delta t \lambda (1 - |\Gamma_1|^2)} = \frac{\rho c}{\lambda} \frac{\partial T}{\partial t} \quad (14)$$

1.4 Definite condition

Definite condition is composed of initial condition and boundary condition. Based on the assumption that the initial temperature is uniform, initial condition can be described as

$$t = 0, \quad T(x, y, z, t) = T_0 \quad (15)$$

Boundary condition can be achieved according to theoretical deduction and experimental induction.

1) Theoretical method

The asphalt mixtures in section I are taken as an example to solve for the temperature gradient at the interface between the heating section and section I. $(0, 0)$ and $(\Delta x_1, 0)$ in the coordinate system (x_1, y) are taken to work out the temperature gradient at the interface, where Δx_1 approaches zero. By Eq. (4) the calculation process of the temperature gradient is

written as

$$\left. \frac{\partial T_2}{\partial x_1} \right|_{wx_1} = \lim_{\Delta \eta \rightarrow 0} \frac{\frac{2(T_0 - T_{wx_1})}{\sqrt{\pi}} \int_0^{\Delta \eta} e^{-\Delta \eta^2} d\Delta \eta}{\sqrt{4\alpha t \Delta \eta_{x_1}}} = \frac{(T_0 - T_{wx_1})}{\sqrt{\pi \alpha t}} \quad (16)$$

So the temperature gradient of the interface AB in Fig. 1 in the coordinate system (x, y) is

$$\left. \frac{\partial T_2}{\partial x} \right|_{wx} = \left. \frac{\partial T_2}{\partial x_1} \right|_{wx_1} = \frac{(T_0 - T_{wx})}{\sqrt{\pi \alpha t}} \quad (17)$$

Similarly, the temperature gradients of the other three interfaces (CD , AD , BC in Fig. 1) in the coordinate system (x, y) can be given as

$$\left. \frac{\partial T_2}{\partial x} \right|_{wx} = - \left. \frac{\partial T_2}{\partial x_2} \right|_{wx_2} = - \frac{(T_0 - T_{wx})}{\sqrt{\pi \alpha t}} \quad (18)$$

$$\left. \frac{\partial T_2}{\partial y} \right|_{wy} = \left. \frac{\partial T_2}{\partial y_1} \right|_{wy_1} = \frac{(T_0 - T_{wy})}{\sqrt{\pi \alpha t}} \quad (19)$$

$$\left. \frac{\partial T_2}{\partial y} \right|_{wy} = - \left. \frac{\partial T_2}{\partial y_2} \right|_{wy_2} = - \frac{(T_0 - T_{wy})}{\sqrt{\pi \alpha t}} \quad (20)$$

2) Experimental method

When establishing a heat transfer model, the accuracy of heat flux density at the interface cannot be guaranteed by the theoretical method influenced by natural factors. Hence, the reverse method is introduced to solve this problem. Temperature values of the interface in different heating stages and positions are recorded in the microwave experiments. Then, morbid values are rejected and dual Lagrange interpolation is applied to fit the temperature data above. Consequently, the model of boundary conditions is built by the experimental method.

2 Microwave Heating Experiment and Simulation

2.1 Microwave heating experiment

In the heating experiment, microwaves emitted by the magnetron enters an excitation cavity and a horn radiation cavity. The required working modes are subsequently produced. Then a new high frequency electromagnetic field radiates directly into the asphalt mixtures through the aperture of the horn antenna. Asphalt mixtures are heated by molecular polarization. A metal net mask is made to avoid the harm of electromagnetic radiation for physical safety. The infrared thermometer is used in the experiment to measure the surface temperatures of the asphalt mixtures^[8].

The initial conditions and structural parameters of the experiment are $T_e = 30.2^\circ\text{C}$, $T_i = 30.4^\circ\text{C}$, $H = 10\text{ cm}$, $L_H = 43\text{ cm}$, $L_E = 32\text{ cm}$, $A_s = 15\text{ cm} \times 12\text{ cm}$, $F = 2450\text{ MHz}$, $P_{in} = 1300\text{ W}$, $t = 600\text{ s}$. Where T_e is the environment temperature; T_i is the initial temperature of the asphalt mixtures; H is the thickness of the asphalt mixtures; L_H is the length of the horn antenna in H-plane; L_E is the length of the horn antenna in E-plane; A_s is the aperture area of the horn antenna; F is the frequency of microwaves; and P_{in} is the input power of the

magnetron.

10×8 grids are adopted to divide the heated surface. Cubic spline functions are applied to fit all the temperature values of the grids measured in the experiments, and the fitting surface is shown in Fig. 2. From Fig. 2 it can be seen that the temperature distribution surface has a comparatively gentle characteristic. The center temperatures in the heating range are relatively higher. However, the values are slightly reduced around the periphery. The temperature gradient is not remarkable and the uniformity has a good effect.

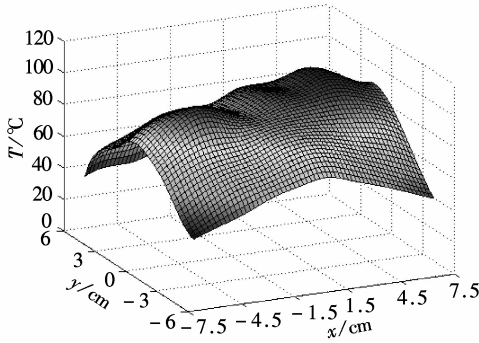


Fig. 2 The experimental temperature distribution on cross-section of asphalt mixtures

2.2 Computer simulation

Calculation shows that the average output radiation power is 616.5W in the experiment of heating a water load according to temperature rise per unit time. The average instantaneous value of electric field intensity is 2 042 V/m without considering the differences of standing wave coefficients in the water load and in the asphalt mixtures. The model of boundary conditions by the reverse method is

$$T|_{x=7.5} = f_x(y, t) = (-0.000\,024\,195y^2 + 0.000\,036\,54y + 0.000\,374\,4)t^2 + (0.020\,716\,9y^2 - 0.022\,532y - 0.285\,55)t + (-5.207\,37y^2 + 4.222\,73y + 119.85) \quad (21)$$

$$T|_{y=6} = f_y(x, t) = (-0.000\,023\,31x^2 + 0.000\,079\,116x + 0.000\,386\,6)t^2 + (0.017\,395\,49x^2 - 0.056\,799x - 0.222\,1)t + (-3.505\,54x^2 + 9.797\,4x + 91.8) \quad (22)$$

PDE toolbox in Matlab is used to solve the heat conduction differential equation. Fig. 3 gives the numerical solution of trans-verse temperatures in the asphalt mixtures. The heat transfer is nonlinear from analysis of simulated temperature distribution. The highest temperature, about 90 °C, is in the central position. The values show little change in the whole surface. However, they are slightly reduced around the periphery. The simulant temperature distribution is basically in accordance with the former experiment. Hence, it is feasible to apply the heat transfer model in this paper to simulate the temperature distribution.

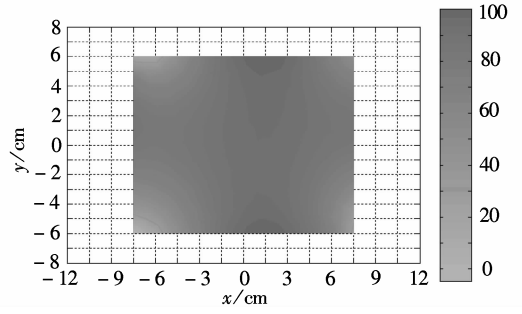


Fig. 3 The simulant temperature distribution on cross-section of asphalt mixtures

3 Conclusion

Heat transfer law of hot in-place recycling has a direct effect on temperature distribution in asphalt pavements. Heat conduction differential equations inside and outside the heating range are respectively built based on the heat conduction principle. Experimental methods to calculate the intensity of radiation electric field can avoid the difficulty of direct measure. Boundary conditions are achieved from theoretical deduction and experimental induction. Visualization of temperature distribution solved by simulation software comparatively accord with the experimental data. The results demonstrate the accuracy and availability of the model proposed in this paper. This paper lays a good theoretical foundation for the research of thermal-electrical coupling and provides guidance in the coming design of heating processes.

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沥青路面微波现场热再生传热模型

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摘要: 为了获得沥青路面微波热再生过程的温度分布规律, 根据非稳态导热理论建立了加热区域内的二维传热模型, 将加热区域外沥青料简化成 4 个半无限大固体分别建立了一维传热模型. 通过加热水负载实验求解了加热沥青料的辐射电场强度. 理论推导出了传热边界条件数学模型, 并提出了采用实验数据拟合反求边界条件的方法. 通过加热实验测出了沥青混合料的温度并拟合出温度场分布, 利用 Matlab 中的偏微分工具箱对传热模型仿真求解, 求得的温度场分布和实验结果相当吻合. 研究结果证实了该传热模型具有较高的精度, 可以直接计算沥青路面热再生过程中的温度分布.

关键词: 沥青路面; 微波现场热再生; 传热模型; 边界条件; 辐射电场强度; 微波加热实验

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