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Microwave heating simulation of asphalt pavements

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ABSTRACT: Microwave heating is a promising heating technology for the maintenance, recycling and deicing of pavement structures. Many experimental studies have been conducted to investigate the microwave heating properties of asphalt mixtures in the laboratory. However, very few studies investigated the application of microwave heating on asphalt pavements. This study aims to simulate microwave heating of paving materials using the finite element method. Results show that the developed three-dimensional model, which couples the physics of electromagnetic waves and heat transfer, shows a great potential for optimizing the design of microwave heating prototypes for pavement applications.

1. INTRODUCTION

Microwave heating has been widely applied in various industrial fields, such as food and construction materials processing. Microwave has the potential to provide rapid, uniform, high efficient, safe and environment-friendly heating technology of materials (Jones et al. 2002, Metaxas & Meredith 2008). Due to the above advantages of microwave heating, there have been increased interests in utilizing microwave heating in the paving industry. Specifically, three main applications in pavement engineering: (i) pavement maintenance, such as crack healing in asphalt, pothole patching; (ii) recycling of the old pavement materials (heating of reclaimed asphalt pavement using a microwave tunnel); and (iii) snow melting or deicing (Wang et al. 2020).

In the conventional heating methods, such as hot-air heating and infrared heating, energy is transferred from the surfaces of the material to the internal by convection, conduction and radiation (Metaxas & Meredith 2008). In contrast, microwave heating is achieved by molecular excitation inside the material without relying on the temperature gradient. Therefore, microwave heating is a direct energy conversion process rather than heat transfer from external heat sources (Wang et al. 2019). This fundamental difference in transferring energy endows microwave heating many exclusive advantages, such as no air emissions or liquid pollutants, speed heating, volumetric heating, selective heating, easier to control and isolation of risk conditions, strict control of programmed heating, etc. (Benedetto & Calvi 2013). Although microwave heating technology was tried and some prototype equipment was developed for paving materials production (Jeppson 1986, Eliot 2013, Benedetto & Calvi 2013) and pavement maintenance (Bosisio et al. 1974, Terrel & Al-Qhaly 1987, Al-Qhaly & Terrel 1988) applications, it is still not commercially used in this field at the present time, mainly due to the high operating costs. Therefore, this study aims to design a microwave heating system for paving materials and pavement structures through finite element method (FEM). The effects of microwave power, operating frequency, and moving speed on the heating efficiency of (asphalt) pavements were investigated.

2. FINITE ELEMENT MODEL OF MICROWAVE SYSTEM

2.1 Multiphysics governing equations

Microwave heating involves electromagnetic waves and heat transfer phenomena. To simulate the electro-magneto-thermal phenomena in a real-time system, the COMSOL Multiphysics software has been utilized for modelling microwave heating in pavements made from asphalt.

Electromagnetic analysis of a medium corresponding to a paving material, such as asphalt mixture, involves solving Maxwell's equations subject to certain boundary conditions. These equations can be formulated in differential form, which can be handled by FEM

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (1a)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1b)$$

$$\nabla \cdot \mathbf{D} = \rho_e \quad (1c)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (1d)$$

To apply the Maxwell equations, the constitutive relations describing the macroscopic properties of asphalt mixture need to be determined. For linear materials, the polarization is directly proportional to the electric field; the magnetization is directly proportional to the magnetic field. Assuming asphalt mixture is an isotropic and linear material, the constitutive equations can be written as

$$\mathbf{J} = \sigma \mathbf{E} \quad (2a)$$
$$\mathbf{D} = \varepsilon \mathbf{E} \quad (2b)$$
$$\mathbf{B} = \mu \mathbf{H} \quad (2c)$$

where **H** is the magnetic field intensity; **J** is the electric current density; **D** is the electric displacement or electric flux density; **E** is the electric field intensity; **B** is the magnetic flux density; ρ_e is the electric charge density; σ is the material electrical conductivity; ε is the material permittivity; μ is the material permeability.

Applied microwave energy is converted into power based on the electric field distribution at a particular location. The absorbed power term is considered a source term in heat transfer equations to calculate transient temperature profile. The equation governing diffusion of heat into continua is as

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_e \quad (3)$$

where ρ is the density; C_p is the specific heat at constant pressure; k is the thermal conductivity; T is the temperature at time t; and Q_e is the internal heat source (absorbed power). The surface of the material exchanges heat with surrounding air by convection expressed as

$$-\mathbf{n} \cdot \mathbf{q} = h(T - T_a) \quad (4)$$

where **q** is the conductive heat flux; h is the surface convective coefficient; **n** is the normal vector on the boundary; T is the transient temperature and T_a is the ambient temperature.

The electro-magneto-thermal phenomenon often encountered in microwave heating is usually solved in a coupled manner. The distributed heat source, which includes resistive heating (ohmic heating) and magnetic losses in **Eq. 5** (Kopyt & Celuch 2007), is computed in a stationary, frequency-domain electromagnetic analysis. Then a transient heat transfer simulation showing how the heat redistributes in the asphalt pavement was followed

$$Q_e = Q_{rh} + Q_{ml} \quad (5a)$$

$$Q_{rh} = \frac{1}{2}\mathrm{Re}(\mathbf{J} \cdot \mathbf{E}) \quad (5b)$$

$$Q_{ml} = \frac{1}{2}\mathrm{Re}(i\omega \mathbf{B} \cdot \mathbf{H}) \quad (5c)$$

where Q_{rh} is the resistive heating of dielectric material; Q_{ml} is the magnetic loss of magnetic material interacting with the magnetic field component of microwave. Re() is the real part of the variable.

2.2 Model definition

The microwave heating unit is a metallic box connected to a microwave source via a rectangular waveguide. The dimensions of the heating unit are 0.3 m (length) × 0.15 m (width) × 0.05 m (height). The waveguide is made of aluminum. To reduce surface losses, the inside walls are coated with copper, a high-conductivity metal. The applied impedance boundary condition on these walls ensures the small resistive metals losses get accounted for. As can be seen in Fig.1, there are two rectangular ports in the heating unit. Only Port 1 is excited by a transverse electric (TE) wave. The TE_{10} mode was chosen at an arbitrary trial frequency of 1 GHz. The thickness of asphalt pavement (2 m × 2 m) is set as 0.2 m. The asphalt pavement layer is modeled as a dielectric material having electrical conductivity of σ = 3.85 × 10^{-7} S/m, relative permeability of $\mu_r = 1.03$, and a relative permittivity of $\varepsilon_r = 5.68$, with a loss tangent of δ = 0.176. The thermal conductivity is k = 1.446 W/(m·K). Furthermore, the density is 2632 kg/m^3 and the specific heat is 756.5 J/(kg·K).

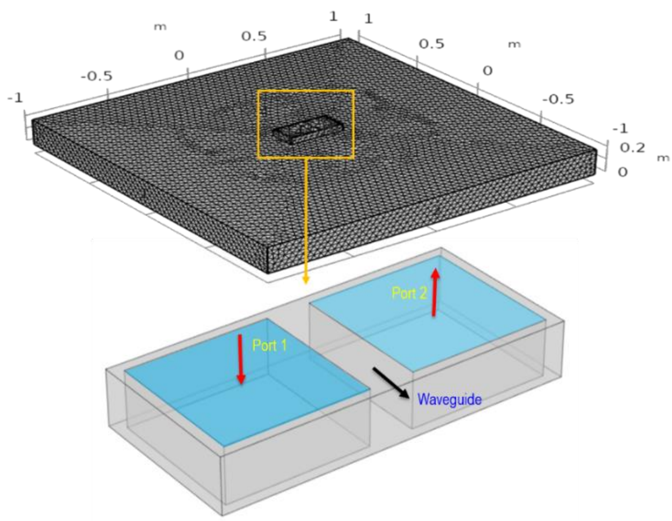

Fig. 1 Model of asphalt pavement and microwave heating unit above pavement surface.

To ensure a relatively high level of simulation accuracy and a reasonable computation time, the domains of the three-dimensional model were meshed with different element sizes. The maximum mesh size in the air domain in the microwave heating unit should be smaller than 0.2 wavelengths. For the asphalt pavement layer, the mesh size was scaled by the inverse of the square root of the relative dielectric constant. In this study, different input power values (1000 kW, 2000 kW, 4000 kW, and 8000 kW) were assigned to the port for the parametric analysis.

3 FINITE ELEMENT SIMULATIONS

Sensitivity analyses were conducted, given the importance to identify the main operational factors that influenced the efficiency of microwave heating. The thermal field distribution of asphalt pavement after 300 s microwave heating with the supplied power of 4000 kW is presented in Fig. 2. Fig. 2b shows the temperature distribution of pavement surface underneath the microwave ports. It shows a special heating pattern which is related to the electromagnetic wave shape. Based on the temperature distribution, it is recommended to move the microwave unit horizontally to achieve uniform heating and avoid repeated heating. Fig. 2c shows the temperature distribution of the selected cross section (indicated by the dashed line) along the depth. It clearly shows the microwave energy attenuated gradually along the depth, resulting in a temperature gradient. The temperature distribution exhibits a pattern of wave propagation in the longitudinal direction.

To quantitatively analyse the effect of supplied microwave power on heating efficiency, point temperature evaluation underneath the center of Port 1 was conducted. Temperature evolution with time with different input powers was presented in Fig. 3. As expected, a higher heating efficiency can be achieved when applying higher supplied power. When the supplied power increased to 4000 kW, surface temperature of asphalt pavement can reach approximately 200°C after 300 s, which is sufficient for pavement maintenance and rehabilitation, etc. However, when applying an input power of 8000 kW, the surface temperature is extremely high after 300 s of heating, which will burn the material. One may argue that applying 8000 kW can reach the required temperature in a very short time. However, this leaves very limited time for the operational works for either maintenance or rehabilitation.

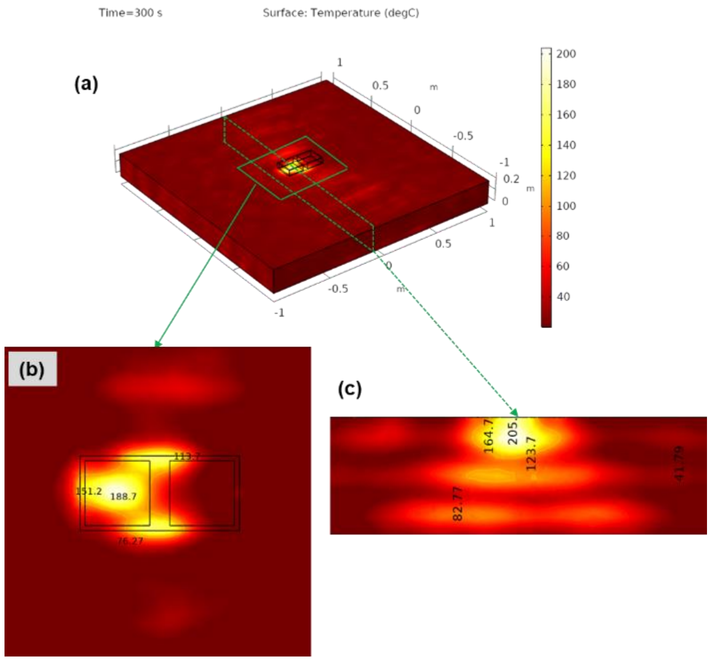

Fig. 2 Thermal field distribution of asphalt pavement after 300 s heating (a) entirety (b) top surface (c) cross section.

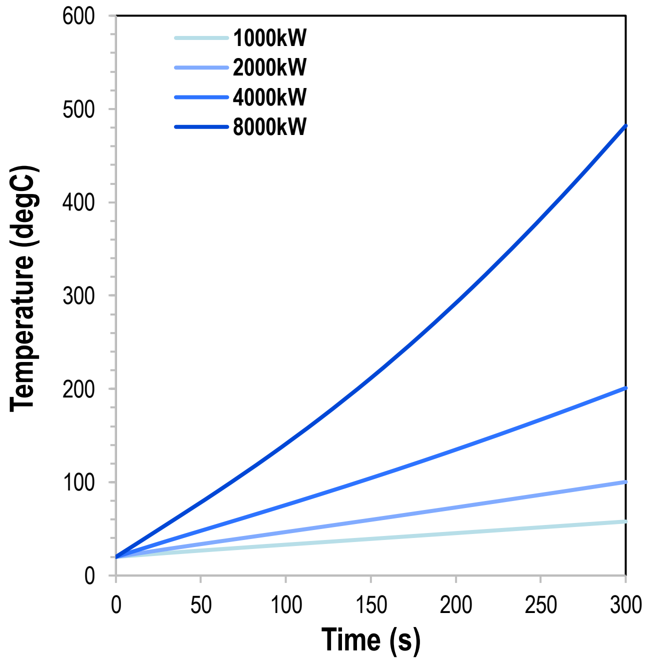

Fig. 3 Temperature evolution with time with different input power values.

As pointed out earlier, microwave energy attenuated along the depth of asphalt pavement. It is important to know how the temperature evolves with the depth of pavement structure. Fig. 4 shows the temperature variation with pavement depth at the location of centre of Port 1. From pavement bottom to surface, the temperature generally shows an increasing trend with clear wavelike fluctuations. The fluctuations are more prominent at a higher supplied power. The formation of temperature fluctuation is because of the harmonic nature of electromagnetic wave propagation. The peak and valley of temperature fluctuation correspond to the peak and valley of propagating wave considering the wavelength of applied microwave is 0.075 m according to Eq. 6. Based on the analyses from Fig. 4, there are two points worthy to be noticed: (1) gradient heating along pavement thickness can be achieved by microwave to effectively control the heating depth; (2) particular temperature fluctuations can be realized through adjusting the microwave frequency to satisfy peculiar functions (e.g., heating certain layers of multilayer asphalt pavement structure).

$$\lambda = \frac{c}{f} \tag{6}$$

where λ is the wavelength, c is the speed of light, and f is the operational frequency.

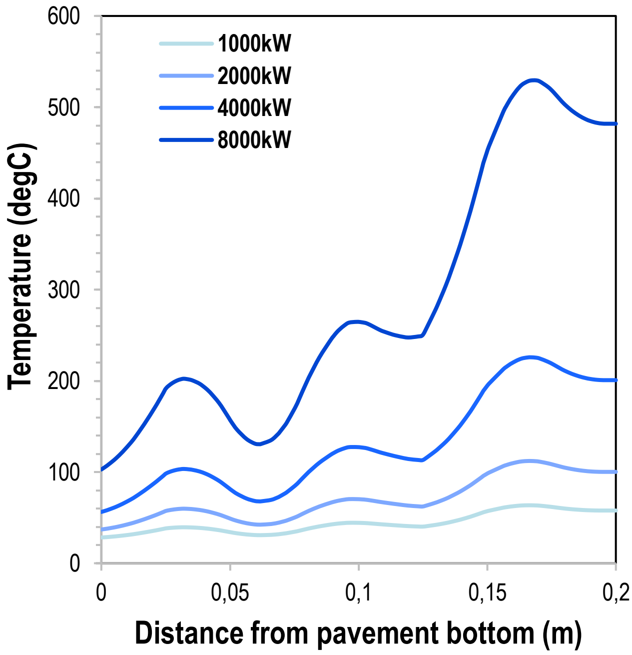

Fig. 4 Temperature development of asphalt pavement along the depth after 300 s heating.

The heat transfer phenomena and the temperature profile along the thickness of studied medium as shown in Fig. 4 coincide with the results obtained elsewhere (Bosisio et al. 1974, Sun 2014).

4 CONCLUSIONS

Based on the study results, the three-dimensional finite element method for microwave heating shows a great potential for optimizing the design of microwave heating prototypes for asphalt pavement applications. Effects of operational parameters on heating efficiency are simulated. A supplied power of 4000 kW at 1 GHz was expected to achieve sufficient heating temperatures without generating excessively high temperatures. Gradient and selective heating of asphalt pavement can be achieved by microwave heating.

For future studies, a moving microwave system should be added to the current mode to investigate the effects of moving speed on heating efficiency. In addition, effects of electro-magneto-thermal properties of asphalt pavements can be examined.

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