Enhancing the Thermal Performance of Electric Cable-heated Pavement by Asymmetrical Thermal Insulation Coating: A Numerical Simulation Study

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Abstract - Recently, there has been a growing emphasis on incorporating energy systems into infrastructures. Among these systems, electrically cable-heated pavements stand out for their ability to melt snow and ice in cold regions during winter. Thermal Insulation Coating (TIC) is a technology employing thermally insulating materials as a spray to coat surfaces. These materials include suspension plasma spraying, silica aerogel, and nanostructured materials. Given that the heat from electrically cable-heated pavements is primarily directed upwards, employing an asymmetrical configuration of TIC in these systems could be advantageous. In this investigation, TIC would function effectively as a thermal barrier, blocking the thermal flux toward deeper and optimizing the whole system's thermal performance. Initially, a numerical model of an uncoated cable-heated pavement system was developed. This model was extended to include an asymmetrical TIC and subsequently its thermal interaction with the pavement structure. The incorporation of asymmetrical TIC has the potential to significantly enhance the energy performance of cable-heated systems. In a comparative analysis of uncoated cable-heated pavements, it was observed that cable-heated pavements had a higher surface temperature under identical conditions. Furthermore, the asymmetrically applying TIC could lead the heat transfer asymmetrically around heated-cable, which enriches the scientific understanding of asymmetrically applying TIC in cable-heated systems embedded in pavements.

1. Introduction

In recent decades, the integration of energy systems within modern civil engineering infrastructures has become increasingly prominent. This integration consists of several unique energy technologies which are implemented in specialized civil applications, including roads, bridges, runways, and buildings. Taking the thermal systems as an example, various energy sources have been utilized to maintain the pavement surface temperature for enhancing the performance of asphalt and cement concrete. Among them, the electric-heated pavement is one of the most convenient ways. Conductive cement concrete, current wire, and induction coils can be installed in the pavement surface layer while contracting. During winter, the ice and snow on pavements can be melted by the systems in cold regions. In addition to the effect of enhancing the road performance, these systems can also significantly reduce transportation hazards.

Regardless of the limited working temperature of the phase change material, the potential polluting possibility of hydronic-heated pavement systems, and high sensitivity to the spray time and the amount of polytetrafluoroethylene coating, the electric-heated systems are more sustainable and reliable. From the view of energy conversion, these systems could be classified into four diverse methods, including Electric Cable-Heated Pavements (ECHP) (which are also called as electric heat tracing systems), conductive concrete heated pavement technology, microwave heating, and the electromagnetic (EM) technique. Due to the simplicity of engineering practice and mechanical sustainability of cables, ECHP is one of the most commonly used methods among these electrical systems.

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Asymmetric energy demands leads to a thermal insulation configuration, especially in some specialized systems for particular functions. In the cable-heated pavement scenario, thermal energy needs to be released/transferred to the pavement surface instead of diffusing it in all directions. Some low thermal conductivity materials have been thus adopted as an insulation layer, such as with foamed concrete [1], heat-insulated foam [2], and thermal insulation paint [3]. Nevertheless, these materials have mostly been used to construct an independent base layer of pavement for heat insulation. The layer can affect the mechanical properties of pavement, decreasing the load capacity and long term sustainability of structure. Furthermore, the asymmetric insulating configuration also serves the purpose of enhancing the energy performance of cable-heated pavements.

Thermal insulation coating (TIC) refers to several specialized materials which are applied to a surface for reducing heat transfer. In some particular areas like in engines, it is also termed as a thermal barrier coating, such as in crystalline oxide materials (e.g. yttria-stabilized zirconia) which have a low thermal conductive (about 2 W·K^{-1}·m^{-1}) [4] in high temperature (up to 1200 °C). Conversely, due to the working temperature of the winter atmosphere and concrete thermal conductive (mostly less than 2 W·K^{-1}·m^{-1}) [5], silica aerogel and hollow spheres have grown in favor [7, 6, 8] as lower thermal conductivity materials.

Aerogel is one of the porous materials that is made of different compounds with ultra-high porosity. Making use of the low conduction of air, silica aerogel can be adding to polymers or binders to decrease the whole spray's thermal conduction. The use of hollow sphere is another dominant technology for insulating heat. Some commercial TIC materials are based on hollow glass spheres and their thermal conductivity can be even less than 0.04 W·K^{-1}·m^{-1}.

This study aims to explore the enhancement of thermal performance in cable-heated pavements through an asymmetrical application of TIC, which fills a notable gap in current studies. Employing a numerical simulation approach, this paper develops models of cable-heated pavement with and without asymmetrical TIC. Our investigation not only promises significant improvements in energy performance for cable-heated systems but also contributes to a broader scientific understanding of the field.

2. Methods of numerical simulation

2.1. Background information

Thermal conduction, convection, and radiation are three primary methods of heating transfer. For thermal conduction, the governing equation used is based on Fourier's law, shown in equation 1.

$$\boldsymbol{q} = -k\nabla T \tag{1}$$

whereas $\boldsymbol{q}$ is the local heat flux density, W/m^2, and k is the material's conductivity, W/(m·K), ∇T is the temperature gradient, K/m.

The thermal conductivity is defined as the ratio of the heat flux density to the temperature gradient. As has been demonstrated above, the thermal conductivity of cement concrete can be assumed to be 1.8 W·K^{-1}·m^{-1}. Whereas, the thermal conductivity of silica aerogel coating and hollow spheres painting is 0.058 W·K^{-1}·m^{-1} [8], which is approximately 1/30 of the thermal conductivity of cement concrete. This is the reasons why silica aerogel & hollow spheres coating can function as thermal insulation materials. Nevertheless, the complete coating will only insulate the heat transfer instead of redirecting energy to surface, as the asymmetrical insulation configuration does in Figure 1.

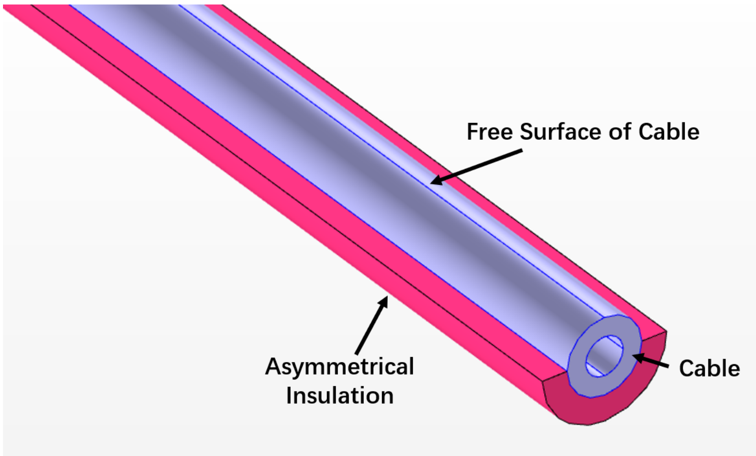


Figure 1 : *Asymmetrical Insulation Configuration of cables*

The main idea of asymmetrical TIC in electric cable-heated pavements is insulating by an asymmetrical configuration. In Figure 1, the thermal insulation paint is sprayed into the "hemisphere" of the heating cables. Instead of $360°$, the upper surfaces of the cables is maintained free to keep better thermal conductivity with the surface of the pavement layer.

2.2. Establishment of numerical simulation

2.2.1. Basic scenario

To simulate the thermal interaction between the pavements and the coated cable-heating systems, a reliable heat transfer model of the pavement is necessary. In this communication paper, COMSOL Multiphysics was used for constructing and simulating the heat transfer model. One of the most typical compositions of the pavement structure in France consists of a surface and a base. Underneath the pavement, there are also formations and supporting soil. As an example of standard newly constructing pavement [9] in France, its structure can be 4 cm of BBSG ("Béton Bitumineux Semi-Grenu", Semi-coarse Asphalt Concrete), 12 cm of EME ("Enrobé à Module Élevé", High Modulus Asphalt) and 25 cm of MTHL ("materiau traite aux liants hydrauliques", Hydraulically Bound Materials). According to the *NF P 98-086 Road pavement structural design*, the materials' parameters are shown in Table1.

	ρ	K_{ng}	thickness	C_{mar}
	kg·m^{-3}	W·K^{-1}·m^{-1}	m	J·K^{-1}·kg^{-1}
BBSG	2350	1.9	0.04	836
EME	2390	2.35	0.12	836
MTHL	2300	1.7	0.25	836
TIC	80	0.058	0.002	835

Table 1 : *Material parameters of different pavement layers*

Normally, a cable-heated system is designed for melting snow and ice over the pavement.

As a result of a variety of climates in different locations, the output power of cable-heated systems is based on the local snowfall, Snow Water Equivalent (SWE), and other relative factors. Typically, the input power is postulated as 350 W per square meter of pavement.

In the numerical simulation model, the scale of representative elementary area for pavement structure can be assumed as 75 cm x 60 cm with an input power of 157.5 W. Frequently, the spacing between two parallel runs of heating cables is 0.1 m, distributed in S shapes. The system is generally placed below the BBSG layer and above the EME layer. In this communication paper, the initial and environment temperature are assumed to be at $0°$C. Due to the sample is assumed to be placed in laboratory, the boundaries of the representative elementary area are conjectured to be that of as natural convection flow heat-exchange. The heat transfer coefficients of external natural convection between solid and air are utilized in COMSOL Multiphysis. Taking all the information above, the model of electric cable-heated pavement was built as shown in Figure 2.

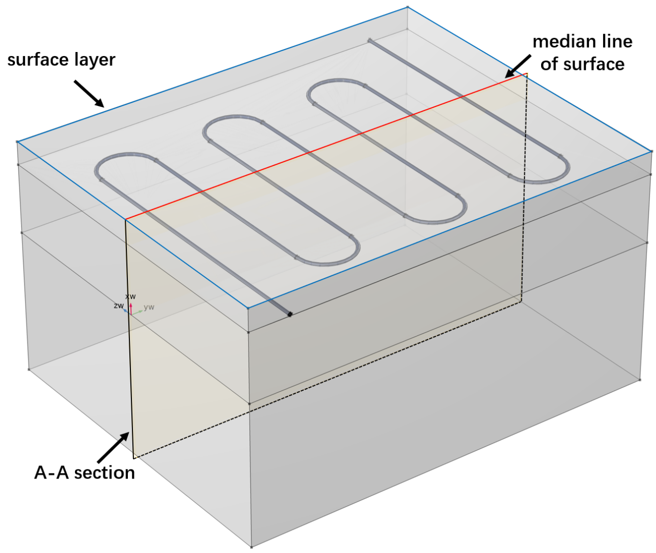


Figure 2 : *Electric cable-heated pavement model (A-A section as the median cut indicated with red line denoted surface median and surface layer in blue)*

In this computational domain, the section labeled A-A represents the median cut, which is highlighted by a red line indicating the surface median, while the surface layer is depicted in blue, as Figure 2 shown. The governing equation of heat transfer in solids is established based on the principle of conservation of energy, as shown in equation 2. Furthermore, the whole domain is divided using the free tetrahedral mesh method, with the mesh refinement next to the cable. The maximum and minimum scales of the mesh blocks are 0.0184m and 0.001m, which has the finest as shown in Figure 3 .

$$\rho C_p \left(\frac{\partial T}{\partial t}\right) + \nabla \mathbf{q} = Q \tag{2}$$

whereas ρ is the density, kg·m^{-3}, C_p is the specific heat capacity at constant stress, J·K^{-1}·kg^{-1}, T is the absolute temperature, K, t is time, s, and q is the heat flux, W/m^2.

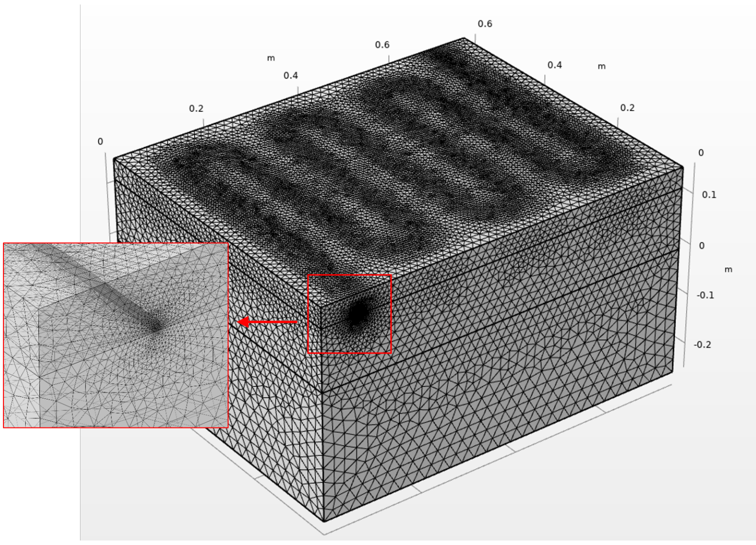


Figure 3 : *Mesh block of Electric cable-heated pavement model*

2.2.2. Cables and asymmetrical TIC

Normally, a carbon fiber heating cable is composed of conductive fibers, electrical insulated polytetrafluoroethylene (PTFE), and a protective sheath with polyvinyl-chloride (PVC). The diameter of the cable is 6mm. As shown in Figure 1, the TIC can be painted as a spray to the half surface of the cables, making the TIC in an "asymmetrical" coating condition. According to Xingni [10], the TIC materials thickness has been assumed as 2 mm. The painted cables are laid aside after the EME layer has been constructed, occupying the spacing of BBSG. In Figure 1, the TIC material is shown in red and the cable in blue.

3. Results

For cable-heated systems in pavement, the basic object is to heat the surface and melt the snow/ice above. Additionally, a fundamental usage strategy of this system is: turning off in most of the time and switching on the systems according to the weather prediction. As a result, the temperature of surface need to be focus and the whole heating process should be concerned. Furthermore, the asymmetrical thermal insulation could directionally lead the heating upward, which means that the temperature around cables also worth to be considered.

3.1. Comparative analysis of surface median line temperatures

The thermal performance of electrical heated-cable can be represented by different variables. Attributable to the scale of cables configuration, it makes sense to consider the temperature of median line as primary one. As depicted in Figure 4, the temperature along median lines' central parts exceeds 21°C after heated, which proved the thermal performance of heating system. Notably, surface with asymmetrically insulated coating on the cables exhibit significantly higher temperature compared to those without. This pronounced disparity highlight the need for further analysis to comprehend the temperature distribution during heating and the effects of asymmetrical insulation coating.

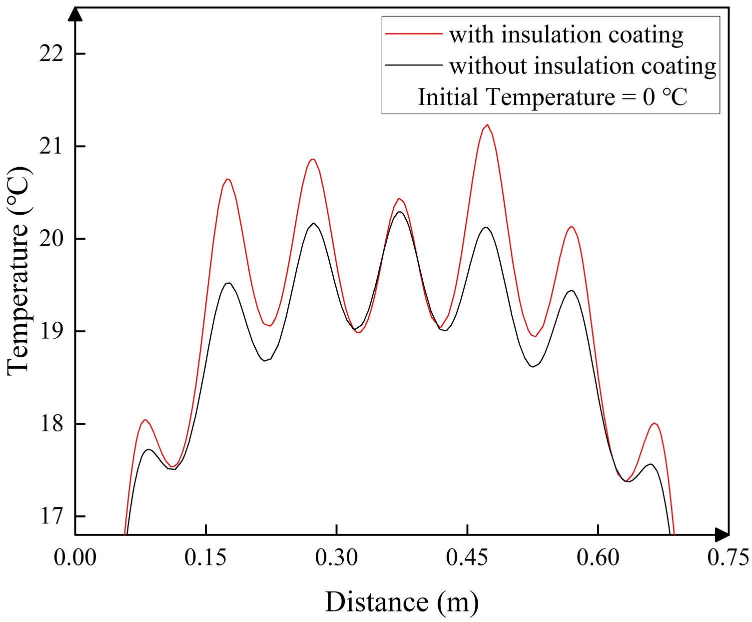
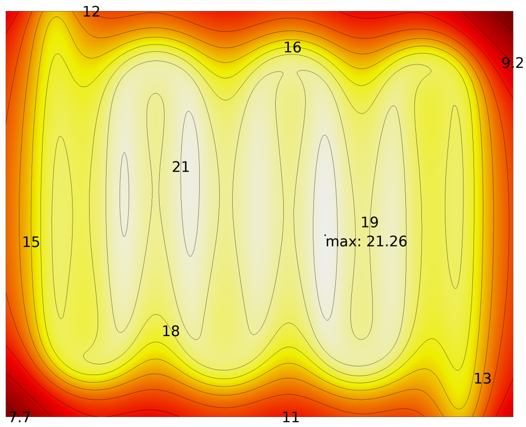


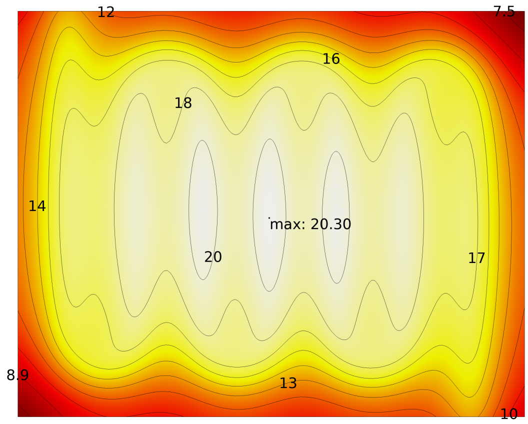
Figure 4 : *Comparative analysis of surface median line temperatures*

3.2. Temperature of surface layer of pavement

For both scenarios (with or without insulation coating), transient state simulation has been performed from 0 to 360 minutes. For the initial condition, the whole structure are set as $0°C$. After 360 minutes heating, the temperature of top-surface rose and distributed as shown in Figure 5.



a. with insulation coating



b. without insulation coating

Figure 5 : *Isothermal lines of surface layer after 360 minutes heating with maximum value*

As depicted in Figure 5 a and b, relatively high and stable temperatures can be seen at the central of surface, which means that the computational area has already enough representative and stability for the systems. Furthermore, the maximum surface temperature of the one with the insulation coating is higher than that without the coating, at $21.26°C$. Comparison of the time-varying maximum surface temperature with and without the asymmetrical insulation coating is shown in Figure 6.

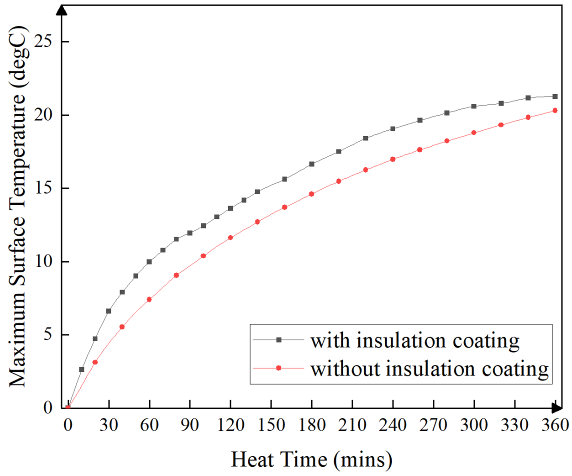


Figure 6 : *The comparison of time-varying maximum surface temperature*

Referring to the figure 6, the maximum surface temperature increases with time. Moreover, it is obvious that the temperature of the pavement with the insulation coating keeps higher than that without, from 0 to 360 minutes.

3.3. The asymmetrical thermal insulation around cable

In principle, an asymmetrical configuration leads to dis-symmetric performance. The TIC under the cable can serve as the barrier for heat, as figure 7 illustrates.

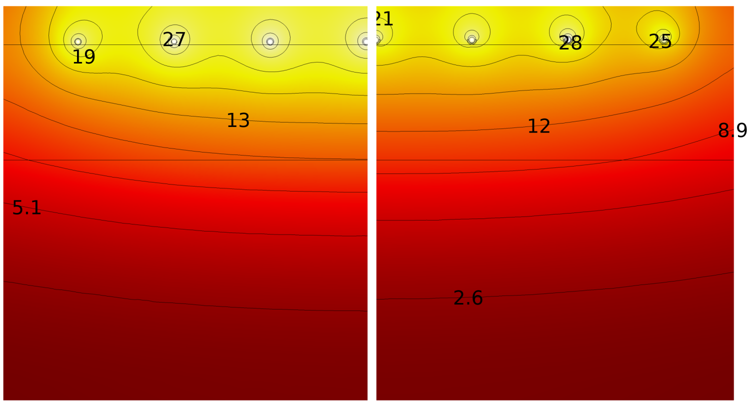


Figure 7 : *Cross-section A-A of two models (right is with insulation coating, left is without)*

In figure 7, the result on the right (with an asymmetrical coating) shows that the isothermal lines near to the cables are near to elliptical in shape and obviously expand upwards. However, the right figure, consisting of the bare cables, makes the isothermal lines more circular in shape. This phenomenon indicates that the asymmetrical thermal insulation around the cable is effective in directly conducting the heat energy up to the surface.

4. Conclusion

This paper concentrates on the asymmetrical TIC of cable-heated systems in pavements. A numerical method is utilized for simulating heat transfer between heating systems and the pavement. Two representative elementary models of real materials and structure are built and analyzed. Compared with the model without insulation coating, the maximum surface temperature is and keeps higher in the model with the coating. Furthermore, the contour and its isothermal lines around the cables indicate an asymmetrical thermal performance. This proves that the insulation coating can transfer the heat directionally, which in turn paves the way for innovative TIC applications. The outcomes of this paper highlight the role of an asymmetrical configured TIC and the enhancing of thermal performance for this coating method. Our research underlines the importance of an asymmetrical configuration in directing conduct heat up towards the surface layer of the pavement.

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