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A Study on Geothermal Snow-melting Technology Based on Chemical PMMA Pavement

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PMMA (polymethylmethacrylate) binder is a two-component polymer material used in road construction. The addition of another component (initiator) to the resin component A results in a rapid secondary crosslinking reaction of the MMA monomer to form a high-strength coating so as to achieve the durable use of the road under special conditions. It can significantly increase the performance of keeping the road surfacedry and anti-skid, to shorten the braking distance by 30-40% or more. However, because of the long winter, the long frozen period as well as the heavy snow in the north, clearing snow has become a difficult task. Moreover, there are more traffic accidents due to the untimely snow-clearing, making a serious impact on the transportation and the security, and the problem of the failure of the slip resistance of the chemical PMMA pavement in the north in winter. Based on the chemical PMMA pavement, a numerical simulation is to be made towards the geothermal snow - melting process using FLUENT, then obtain the temperature field of the snow on the road and the snow-melting law of the interface. According to the size of the radiating pipe's diameter, the spacing and depth of the buried pipes, comparative study is to be done to offer some reference value to the road design with geothermal snow-melting technology.

1. Introduction

Nowadays, the PMMA pavement is widely used due to its advantages in summer including the good anti-skid performance and the excellent performance of chemical resistance. PMMA (polymethylmethacrylate) is a two-component polymer material used in pavement construction. The addition of another component (initiator) to the resin component A results in rapid secondary crosslinking of the MMA monomer to form a high-strength coating to achieve a durable use of the road under specific conditions, which can significantly increase the performance of keeping the pavement dry and anti-skid in rainy days, and shorten the braking distance by 30-40% or more. However, the chemical PMMA pavement faces the problem of the failure of the slip resistance in the north in winter. Because of the long winter, the long frozen period as well as the heavy snow in the north, clearing snow has become a difficult task. Moreover, there are more traffic accidents due to the untimely snow-clearing. At present, the main method to clear snow in the north of our country is to clear snow with mechanic equipments after using the thawing agent. The chemical compositions, such as the potassium acetate and chlorine salt in the thawing agent can cause pavement and steel corrosion. Meanwhile, the soil and water pollution, the soil salinization, the death of plants in the greenbelts as well as the serious damage to the fresh water system can be caused. There are many disadvantages of the mechanical snow removal equipments such as the uneconomical cost, the severe damage to the road surface in the process of clearing snow, the unthoroughness, and easily causing the traffic interruption.

In recent years, the energy conversion snowmelt technologies (Zhao, 2015), including utilizing the solar energy, the geothermal energy, the electric energy and so on, have been applied in many countries in the world such as the United States of America, Canada, Swede and other countries. The main thought is to utilize energy to achieve the aim to melt snow such as the geothermal energy, the solar energy, the electric energy, the high-temperature water and so on (Jorge et al., 2015; Jorge et al., 2015; Zhao and Chen, 2013;

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Zhang, 2009). Utilizing the soil source, the ground source and heat pump to melt snow, with the aqueous solution which is added into the anti-freeze solution being the heat transfer fluid, the heat in the soil is to be transferred to the radiating pipes beneath the road surface, then to the road body, and finally the moving heat make the snow melt (Ahmed, 2009; Brandel, 2006; Pinel et al, 2011). In this way, the aim to remove snow is to be achieved. Meanwhile, the optimal effect of the chemical PMMA pavement is to be achieved as well.

2. The working principle of the system

2.1 The working principle

The geothermal snow melting system consists of three parts. The first one is the snow melting equipments of the road surface, which are buried equidistantly under the road surface with L-shaped radiating pipes. The distance between the pipes is set to be 150-350mm, the depth of the buried pipes is generally set to be 50-100mm, and the diameter of the pipes 20-35mm. The second part is the buried pipes heat exchanger. It transfers heat with the underground soil by the heat transfer fluid in the circulating water pump. The third part is the circulating water pump, which transfers the heat-transfer fluid that has exchanged heat through the circulating water pump to the radiating pipes buried beneath the road, so as to achieve the goal of melting snow. The working diagram of this system is as Figure 1.

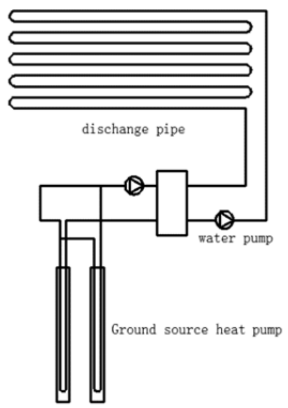

Figure 1: The geothermal snow-melting system diagram

2.2 Mathematics model

The column heat pipe heat exchanger, the expression form of thermal conductivity equation in Cylindrical Coordinates is as follows, (Zhao andFu, 2016),

$$\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{r\partial r^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

The momentum conservation equation is:

$$\rho_0\left(\frac{\partial u}{\partial \tau}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=F_x-\frac{\partial \rho}{\partial x}+\eta\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

The snow melting process is an equation with phase changes and it is an unsteady model. In the equation

$$\rho\frac{\partial H}{\partial t}=k\nabla^2 T \tag{3}$$

$$H=h+\Delta H\ ,\quad h=h_{ref}+\int_{T_{ref}}^{T}c_p dT\ ,\quad \Delta H=\beta L\ ,\quad \beta=\begin{cases}0, T<T_{melt}\\ 1, T>T_{melt}\end{cases}$$

in which ρ means density, *t* means the time of solidification, H means the enthalpy at any time, h_{ref} means the benchmark enthalpy, h means the initial enthalpy, ΔH intends the phase change latent heat of phase, L means the phase change latent heat of the matter, β means the liquid fraction, t_{melt} means the phase-transition temperature, c_p means constant-pressure specific heat, k is the coefficient of heat conductivity, and the letter T refers to the temperature in the snow at any time.

2.3 The establishment of the calculating model

Generally, system calculation is a sophisticated process which is hard to solve due to many complicated factors. Thus, the simplification of the models seems extremely important. To make it easy to calculate and analyze without losing the meaning, some reasonable assumptions can be made as follows:

(1) Due to the heavy clouds during snowing and the extremely low absorption rate of snow to the thermal radiation, the effects of solar radiation are to be ignored.

(2) Regardless of the evaporation of the snow while it is melting.

(3) Assume the heat conductor of each layer has a uniform distribution.

(4) Regardless of it that the radiator pipes transfer the heat downwards.

(5) As for the model's structure, the length of the pipe is far longer than the diameter. Thus, the heat transfer of the temperature field in the length direction is to be ignored

(6) Assume that the performance distribution appears almost the same when the heat radiation system is buried beneath the road, regardless of the edge distribution.

According to the assumption above, the geothermal snow melting system is to be simplified as a calculating model on the triangular mesh. The thickness of snow is made 10mm, and the mesh number 2472. To improve the calculation accuracy, the mesh near the radiating pipes is supposed to be uniform as far as possible.

3. Numerical simulation and analysis of the geothermal snow melting system

3.1 The simulation of the temperature field of the road surface

The core evaluation index of geothermal snowmelt is the snow melting time, but the melting time of road surface is determined by many external factors, such as temperature, relative humidity, wind speed and radiation. The melting time is also influenced by factors related to the heat conduction of the radiating pipes include the heat conduction performance of the road surface, the material of the radiating pipes, the diameter of the pipes, the pitch between pipes and the buried depth. The melting time is also linked with the heat transfer performance of the heat exchanger of the buried pipes, and the fluid temperature of the heat carrier.

The following design conditions should be selected while conducting the simulation. The external temperature is 268.15K, the wind speed is 10m/s, the tube spacing is 300mm, the depth of the buried pipes is 50mm, the temperature of the heat transfer fluid is 333.15K, the coefficient of the thermal conductivity of the concrete is 2.4W / (m • K), the initial temperature of the concrete is 270.15K, and the initial temperature of snow is 268.15K (external environmental temperature). The material of the radiating pipes is made to be DN25 galvanized iron pipes, whose outside diameter is 25mm and thickness is 2.3mm. The heat transfer coefficient is 80W / (m • K), and the external convective heat transfer coefficient is 50W / (m^2 • K).

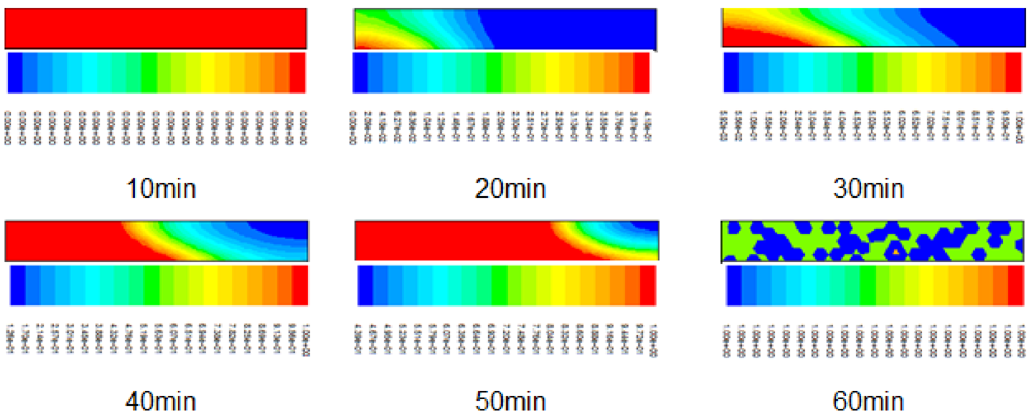

Figure 2: The cloud figure of the proportion distribution of the solid-liquid phase

The snow-melting process of the geothermal energy is simulated numerically. Fig.2 is the snow-melting interface and the distribution of solid-liquid phase in each period. It can be seen from the figure that the snow melting interface changes with the time from the solid state to the solid-liquid two-phase state, and finally to the liquid state in the process of snow melting on the road surface. The warm-up process of the road surface is completed in about 20 minutes, and the snow began to melt on the road. From the cloud figure, we can see that the layer of snow closer to the buried pipe first melted, while the snow which is away from the radiating pipe melted later. About 60 minutes later, the snow on the road melted completely.

Figure 3 shows the temperature distribution during the snow melting process. It can be seen from the figure that the temperature distribution is gradually changing along the radial direction of the pipe. The temperature of the area near the heat radiating pipe is obviously higher than that away from the pipe. With time going, the snow on the road of the whole area all melt in 60 minutes or so. The snow melting effect appears good.

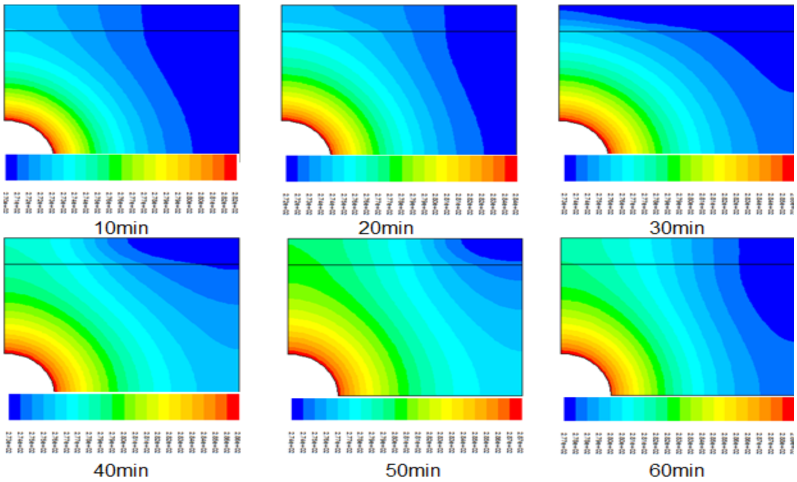

Figure 3: Temperature Distribution at Different Moments

The snow on the road surface melted thoroughly in about 60 minutes, from which it can be seen that the effect of the snow melting is favorable.

3.2 The relationship between the time that the snow melting needs and the parameters

As Figure 4 reflects, the depth of the buried radiating pipes beneath the road is 0.05 meters. When the external temperature is -5°C, the melting time changes with the spacing between the radiating pipes. It can be seen from the figure that the time needed for snow melting increases with the spacing increasing. When the spacing is less than 0.3 meters, the time required for snowmelt changes slightly. While the spacing is more than 0.3 meters, the time for snowmelt improves a lot. It can be seen that the spacing between the radiating pipes has a great influence on the snowmelt time. So when the snowmelt system is designed, the choosing of the spacing between the radiating pipes should not be too far, within 0.3 meters the best. Meanwhile, it can be drawn from the figure that under the condition of the same spacing, it is not obvious for the influence on the snowmelt time to take different values of the pipes' diameter. That is to say, although the increasing of the diameter can shorten the snowmelt time to some extent, the snow melt effect will not be improved if the spacing and the diameter are increased at the same time.

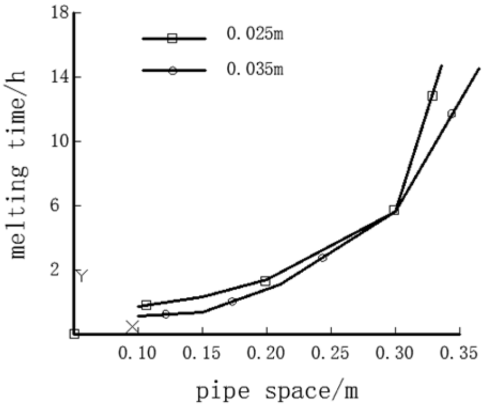

Figure 4: The relationship between the melting time and the distance in the case of different diameters when the buried depth is 0.5m.

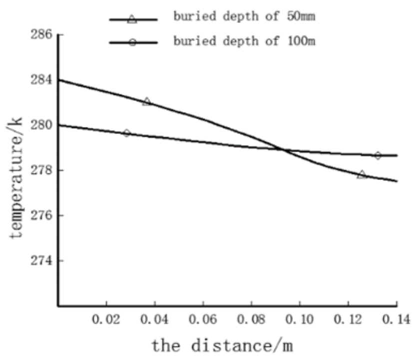

Figure 5: Comparison of the pavement's temperature field with the depth 50mm and 100mm respectively

Fig. 5 reflects the comparison of the temperature field of the road surface when the fluid temperature is 30°C, the distance of the radiating pipes is 0.3m, and the buried depth is 50mm and 100mm respectively, as the figure shows. It can be seen by comparison that when the depth of the pipe is 50mm, the temperature of the pavement above the radiating pipe is the highest, which is 2.6K higher than the temperature of the pavement above the radiating pipe with the buried depth 100mm. As the horizontal distance increases, the depth of the pipeline is shallow, resulting in a fast temperature decay, large temperature fluctuations, and vice versa. At a horizontal distance, where the distance is approximately 0.085 meters above the center of the pipe, the temperatures are equal.

4. Conclusion

Using the heat pump and the ground source in geothermal energy to melt snow, take the aqueous solution that is added antifreeze solution as the heat carrier fluid, transfer the heat of the soil to the radiating pipes lying beneath the road, and then pass to the road body. The final upward moving heat will melt snow, and ultimately achieve the purpose of melting snow, making the chemical PMMA pavement achieve the best results.

(1) The simulation results show that the phase diagram and the temperature distribution in the melting process. As for 12-hour continuous snowing, and the precipitation reaches the level of 3-5.9mm, the snow on the road can completely melt in 60 minutes after the snow using the geothermal snowmelt technology

(2) The laying distance between the radiating pipes has a great influence on the snow melting time, and the time required for the snow melting increases with the increasing of the laying distance of the radiating pipes beneath the road surface. When the pipe spacing is less than 0.3m, the change of the time required for snowmelt is not obvious. But when the pipe spacing exceeds 0.30m, the time required for snow melting is increased, so the spacing of radiating pipes should not be too big when the system is designed, within 0.3m the best.

(3) When the buried depth of the radiating pipes is 50mm and 100mm respectively, the temperature field of the road surface is compared. It can be seen from the comparison that when the depth of the buried pipe is 50mm, the temperature of the pavement above the radiating pipe is the highest, which is 2.6K higher than that when the buried pipe depth is 100mm. With the increase of the horizontal distance, the temperature of the road surface decays faster and the temperature fluctuations are relatively larger when the pipe is buried shallowly and vice versa. At the horizontal distance, the temperatures are equal where the distance is approximately 0.085 m above the center of the pipes.

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