Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-3585

Effect of thermal properties on pavement surface temperatures

L`effet des propriétés thermiques sur la formation de givrage de surface

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ABSTRACT
This paper discusses pavement surface temperatures and the effect of thermal properties on road surface icing. Friction measurements as well as surface temperature modeling and the effect of an insulation layer and its depth to pavement surface temperatures are also discussed.

RÉSUMÉ
Ce document discute des températures de surface des chaussées et de l`effet des propriétés thermiques sur la formation de givrage de surface. On discute de la mesure de la friction ainsi que de la modélisation des températures de surface. L`effet d`une couche isolante et de sa profondeur sur la température de surface des chaussées sont aussi discutées.

1 INTRODUCTION

One way to prevent frost damage to road pavements is by means of the embankment insulation. The optimal location of the insulation for frost protection purposes is at the top of the embankment just below the AC layer. For reparation and reconstruction works, this location is also the most cost effective, due to the reduced need for excavation and filling. It has been found, however, that such a location of the insulation has a harmful disadvantage: under certain circumstances, icing can unexpectedly be formed on the road, causing severe problems for traffic.

In Sweden polystyrene insulations in road construction were examined in 70's and 80's (Gandahl, 1981). It was observed that temperatures on an insulated road surface were lower and the surface was more exposed to icing than having a conventional, mineral road embankment. Based on the results of the tests it was decided that at least 500 mm covering should be used above the insulation in Sweden. In Finland the road authorities ended up to a required thickness of 700 mm for the covering; at the same time in Norway only 300 mm was required.

A few years ago, the Exclay Internordic Geoproject called "LWA-geolight" was initiated by Optiroc Group aiming at research into an overall utilization of expanded clay (termed as exclay, LWA or LECA for Lightweight Expanded Clay Aggregate) in road embankments. Two test sites were constructed: one in Tuupakka, near Helsinki, Finland and one in Trondheim, Norway. The Helsinki University of Technology is involved in the project, performing friction and temperature measurements on the test road at Tuupakka in order to gain a better understanding of the physical behaviour of the whole road structure. In Tuupakka three LWA-insulated test structures were compared with each other and with one "reference" structure, which was constructed using conventional materials. The insulated structures had total thickness of 350mm, 500mm or 700 mm of gravel- and AC-layers over the LWA-insulation layer (see Table 1).

Heat transfer analyses of the pavement was performed in the project by Åke Hermansson using a numerical model, which was introduced in his doctoral thesis (Hermansson 2002) and is referred in this paper. Preliminary results of the tests were previewed by Gustavsson Ravaska and Hermansson (2001) in Cold Regions Engineering Conference in Alaska and details are more extensively reported by Gustavsson et al. (2002) and the whole project represented by Watn et a. (2003).

In his Phd-thesis Jean Côté (2000) found out that the surface cooling rate increases rapidly when all of the granular material placed above the insulating layer is frozen. Then the absence of latent heat release makes the pavement surface more sensitive to rapidly changing meteorological conditions. Before the frost front reaches the insulation, almost no difference can be seen in the behavior of different structures. Côté also suggests the use of frost point (T_f) instead of dew point (T_d) as a criterion to hoarfrost formation because it was shown, that hoarfrost formation occurs already when the surface temperature is less than the frost point. The value of frost point is somewhat higher than the value of dew point ($T_f \sim 0{,}9T_d$), which means that hoarfrost formation begins before the surface temperature is below the dew point. The structures in Côtés studies consisted of 50 mm polystyrene insulation placed in a depth of 70 or 210mm below the surface of the road.

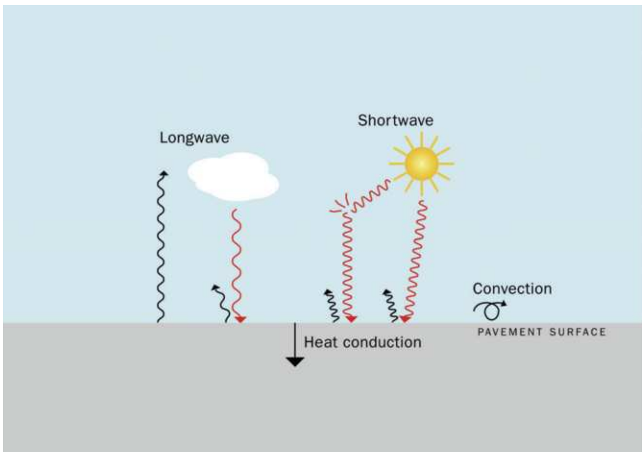

Figure 1. The temperature of the pavement surface is affected by shortwave solar radiation, longwave radiation outgoing from the pavement surface, counter radiation, convection losses and heat conduction in the pavement.

2 THEORY

The heat balance between the air/space and pavement surface is schematically depicted in Figure 1. Solar radiation, wind and air temperature are climate factors, which are of great importance for the temperature of the pavement surface. Other factors of great importance are long wave counter radiation and radiation outgoing from the pavement surface.

Radiation from the sun is short wave and it might be direct or diffusely scattered due to clouds etc. Some of it is reflected back to space depending on the albedo of the surface. Radiation from the pavement to the space is long wave. Some of this is absorbed by atmosphere and partly emitted back as counter radiation. Convection due to wind, as well as heat conduction into the ground are also important factors for the surface temperatures.

2.1 *Radiation balance*

2.1.1 *Out going long wave radiation*

The earth surface is assumed to emit longwave radiation as a black body. Thus, the outgoing longwave radiation follows Stefan-Boltzman law, eq (1),

$$q_r = \varepsilon \sigma T_s^4 \tag{1}$$

where q_r is the outgoing radiation in W/m^2, ε emission coefficient, σ is Stefan-Boltzman constant $5.68 * 10^{-8} W/(m^2K^4)$ and T_s is the surface temperature in K.

2.1.2 *Longwave counter radiation*

The atmosphere absorbs radiation and emits it as longwave radiation to the earth, so-called counter radiation. Counter radiation absorbed by the pavement surface can be calculated as proposed by Solaimanian and Kennedy (1993), eq (2).

$$q_a = \varepsilon_a \sigma T_{air}^4 \tag{2}$$

where q_a is absorbed counter radiation in W/m^2.The factor ε_a describes both the pavement surface absorptivity for longwave radiation and the amount of clouds, and T_{air} is the air temperature, 2 m above the surface, in *K*.

The factor ε_a can be set to 0.7 a clear day, but it varies with the weather. In Hermansson (2001) a sensitivity analysis for the parameter ε_a is described.

2.1.3 *Short wave radiation*

The surface of the sun has a very high temperature, approx. 6000 *K*, and it therefore emits radiation of high frequency (short wave). Part of this radiation is diffusely scattered in the atmosphere of the earth in all directions and the diffused radiation reaching the earth is called diffuse incident radiation. Radiation from the sun, reaching the earth surface without being reflected by clouds, absorbed or scattered by the atmosphere, is called direct short wave radiation. The distribution of direct and diffuse radiation is dependent on the weather. Clear weather causes a larger portion of direct radiation than if the weather is cloudy.

When the short wave radiation reaches the pavement surface a portion is reflected and the rest absorbed by the pavement. The portion reflected is equal to the albedo of the pavement surface. Albedo is supposed to be equal for diffuse and direct short wave radiation.

In the model proposed in this paper, short wave radiation is given as input data. The short wave radiation can be calculated as described in Hermansson (2000) or, as in this paper, by means of measured values.

2.2 *Convection*

The convection losses from the pavement to the atmosphere can be calculated according to Solaimanian and Kennedy, eq (3).

$$q_c = h_c (T_s - T_{air}) \tag{3}$$

where q_c is the loss energy to the air in W/m^2. The parameter h_c depends partly on the surface temperature and to the major degree of the wind velocity. Equations for h_c in winter and summer conditions are presented in Hermansson's thesis (2002)

2.3 *Heat balance*

The described phenomena give the energy absorbed and emitted by the pavement surface. Heat is also exchanged with the ground below, through classical heat transfer. This can be dealt with by means of a finite difference approximation of the heat transfer equation.

3 THE SIMULATION MODEL

The simulation model uses climate data in the form of hourly values for incident short wave radiation, air temperature and wind velocity. The portion reflected, of the incident short wave radiation is given by albedo of the pavement surface. The remaining portion is absorbed by the pavement surface, which causes the surface temperature to rise. Long wave radiation is calculated by eq. (1) and (2), where (1) describes outgoing radiation from the pavement surface and (2) the radiation absorbed by the pavement surface. Convection losses are calculated by eq. (3).

For the calculation of heat transfer, the ground is divided into cells, thinner near the surface and thicker at a deeper level, where temperature variation is less. Each cell is assigned values for temperature, porosity and degree of water saturation, of which only the temperature varies during the simulation. Thermal conductivity and thermal capacity are calculated according to Sundberg (1988), using information of water content, porosity, soil material and bulk density.

Each cell is given a temperature at the start of the calculation. The model then calculates a new temperature for each cell - several times for each simulated hour. This is done in accordance with a generally accepted heat transfer theory, i.e. heat flows from warmer to colder cells in relation to temperature difference and thermal conductivity. The temperature change depends in its turn on the amount of energy received and the thermal capacity of the material in the cell. During the calculations, the exchange of energy of the uppermost cell through the pavement surface in the form of radiation and convection is also handled. The cell division is made down to a depth of five meters below the surface where the temperature is supposed to be constant, at a level of the annual mean air temperature.

3.1 *Input data to the simulation*

For the simulation, usually hourly values for solar radiation, air temperature and wind speed are used. For this study, the air temperature was monitored every 3 hour right at the test section. During 3 a.m. to 6 a. m. the air temperature was measured every 1.5 hour. Horizontal solar radiation was measured hourly at the Helsinki airport located 5 km north east of the test section. Wind speed is very essential for pavement surface temperature during sunny summer days when the surface temperature differs much from the air temperature. This is not the case during winter and as no wind speed measurements were available, the simulation was performed assuming the weather to be calm.

3.2 *Comparison between measured and calculated temperatures*

In the previous sections it has been described how the mathematical model has been built up and how values essential for different quantities used in the model have been chosen.

Running the model results in calculated temperatures. For comparison, measured temperatures at depth of 20 mm were compared to the calculated. Agreement between measured and calculated temperatures was quite good from November 2000 to and the beginning of February 2001. During February 17 to March 13 the agreement of measured and calculated values were not as good. During this period the pavement is frozen all the time according to measurements. Calculated temperatures though, oscillate a lot and indicate thawing of pavement surface at several occasions during the same period of time. An explanation to this disagreement might be that the section was not completely cleared from snow. Having a more or less white surface the pavement does not absorb as much solar radiation as expected in the model where the surface is supposed to be dark. There are other possible explanations to the disagreement – solar radiation was not measured right at the location, and perhaps is not quite representative.

Table 1. Material parameters and layer thicknesses for modeled structures.

Structure	Dry density (kg/m3)	Water content (vol) %	λ_f frozen W/mC	λ unfrozen W/mC
Reference normal				
100 mm AC	2200	5	1,5	1,5
1700 mm gravel	2000	15	2	1,9
Reference dry				
100 mm AC	2200	2	1,5	1,5
1700 mm gravel	2000	4	0,8	1,1
350mm over LECA				
100 mm AC	2200	5	1,5	1,5
250 mm gravel	2000	15	2	1,9
700 mm LECA	400	5	0,12	0,12
500mm over LECA				
100 mm AC	2200	5	1,5	1,5
400 mm grave	2000	15	2	1,9
1700 mm LECA	400	5	0,12	0,12
700mm over LECA				
100 mm AC	2200	5	1,5	1,5
600 mm gravel	2000	15	2	1,9
700 mm LECA	400	5	0,12	0,12

4 EFFECT OF MATERIAL PROPERTIES

In Tuupakka test site three LWA-insulated test structures were compared with each other and with one "reference" structure, which was constructed using conventional materials. However, to study the behavior of a drier structure, one additional structure, 'reference dry', was designed, to be compared with the others, by modeling. So, in the modeling study, five different structures, were tested by running the simulation model, using measured climate data from Tuupakka. Material properties and layer thicknesses for simulation where chosen according to Table 1 (where λ is heat conductivity).

Figure 2 displays the calculated surface temperatures during the period December 20 –December 21. Here we can see the effect of the installation depth of insulation layer on the surface temperatures: the surface temperature of the insulated road structures are 0,5...1,0^{o}C colder, than the reference road and the coldest from the three insulated pavements is the one, which has only 350 mm covering depth over the insulation. It can also be seen from the figure that the imaginary structure 'reference dry', which has reduced amount of water in the asphalt concrete and gravel layers, is as cold as the coldest insulated structures.

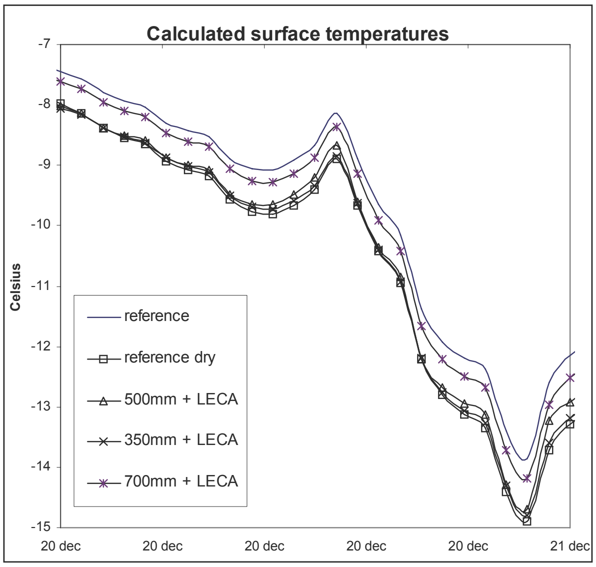

Figure 2. Calculated surface temperatures during December 20 – December 21 with the Tuupakka climate data as input.

5 TEMPERATURE AND FRICTION MEASUREMENTS

The test sections at Tuupakka were equipped with all together 34 temperature sensors. The highest sensors were situated at a nominal depth of 20 mm below the AC surface. Air temperature was measured at 2 meters hight over the road surface. Finnish Meteorological Institute provided the solar power data, measured at Helsinki-Vantaa airport. Relative humidity and dew point temperature were measured at Helsinki-Vantaa airport by Finnra's Road Weather Service.

When slippery conditions were expected also surface friction measurements were done. Friction was measured mostly by two different methods. Both VTI's (Swedish National Road and Transport Research Institute) Portable Friction Tester (PFT) and the Createc C-Trip were in use.

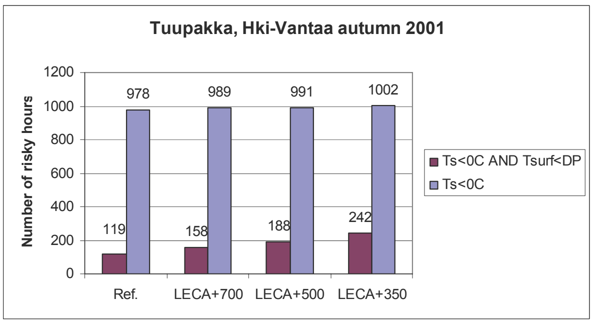

Figure 3.Time that road surface temperature is below 0^{o}C and time that it is below 0^{o}C and below the dew point temperature, based on modeling.

6 ICING RISK EVALUATION

To evaluate the risk of icing and slippery conditions, the time was calculated for different sections that road surface temperature was

– below 0^o C and
– below 0^{o}C and below the dew point temperature.

This evaluation was performed for both the measured and modeled surface temperatures. Figure 3 shows graphically the results of the icing risk evaluation based on the abovementioned criterions using modeled surface temperatures and calculating number of these risky hours.

The time that the road surface is below 0°C, was first suggested for icing risk evaluation criterion, but as can be seen from Figure 3, there is almost no difference between the "number of risky hours" for different structures, using this criterion. When the dew point is added to the criterion quite, obvious relationship between icing risk and installation depth of insulation is found. The icing risk of different structures can be modified to relative icing risk by giving value 1.0 for the reference structure. In Figure 4 the relative icing risks for different structures, based on modelled and measured surface temperatures and using the dew point criterion are presented. As can be seen, the results based on measurements and modeling are very similar and icing risk seems to be very much in correlation with installation depth of the insulation. Also the friction measurements supported these conclusions.

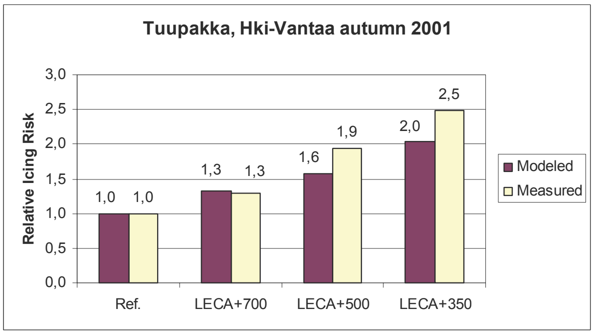

Figure 4. Relative icing risk based on modelled and measured surface temperatures using the dew point criterion.

7 CONCLUSIONS

Pavement surface temperatures can be modelled with quite good accuracy, if air temperature, solar radiation, wind speed and thermal properties of the road are known. In winter good correlation with measured surface temperatures can be achieved even without wind speed data, but in summer the effect of convection is very significant.

If material with low heat conductivity (e.g. insulation) is used near to the surface of pavement, icing risk is increased. To evaluate the risk of icing and slippery conditions, the time can be calculated, that road surface temperature is below 0°C and below the dew point temperature, because in these conditions hoarfrost can be assumed to be accumulating on pavement surface.

Also other thermal properties of the pavement materials affect a lot to the thermal behavior of road surface. Based on literature and modeling, the amount of moisture in the layers near the surface, has also remarkable effect on the icing risk of a road.

Côté & Konrad (2002) suggest the use of frost point (T_f) instead of dew point (T_d) as a criterion to hoarfrost formation because it was shown in his thesis, that hoarfrost formation occurs already when the surface temperature is less than the frost point. The former mentioned dew point criterion was however used in this study.

ACKNOWLEDGEMENTS

This research work was funded mainly by Nordisk Industrifond and Optiroc Group. The author wishes to acknowledge the contributions of all participants of the project in Finland and other Scandinavian countries.

REFERENCES

Côté, J. 2000. Influence d'un isolant thermique sur la sensibilité au verglas des routes. Ph.D Thesis, Department de Génie Civil, Université Laval, Quebec.

Côté, J. & Konrad, J.-M. 2002. A field study of hoarfrost formation on insulated pavements. Canadian Geotechnical Journal 39. pp 547-560.

Gandahl, R. 1981 Plastic foam insulation of roads. Frost resistance capacity, partial insulation and frost heaving, special transitions, icing and economy. VTI rapport 214A.

Gustavsson, H.., Ravaska, O. Hermansson, Å. 2002. The Effect of Insulation on Road Surface Icing.. 11th International Conference on Cold Regions Engineering, Cold Regions Impacts on Transportation and Infrastructure, Anchorage, Alaska, 20-22 May 2002 , ASCE, pp. 278-289.

Gustavsson, H., Valtonen, J., Levomäki, M., Hermansson, Å., 2002. The Effect of LWA-Layer on Pavement Icing. LWA-Geolight - project. 79p. SINTEF, Trondheim

Hermansson, Å., 2001. A Simulation Model for the Calculation of Pavement Temperatures, Comparisons between Calculated and Measured Temperatures. TRB Annual Meeting 2001.

Hermansson, Å., 2002. Modelling of Frost Heave and Surface Temperatures. Luleå University of Technology, Doctoral Thesis.

Johansen, Ö. 1975. Varmeledningsevne av jordarter. Institutt för Kjölteknikk, 7034 Trondheim-NTH, Norge.

Solaimanian, M., and Kennedy, T. W., 1993. Predicting Maximum Pavement Surface Temperature Using Maximum Air Temperature and Hourly Solar Radiation. Transportation Research Record 1417:1-11.

Sundberg, J., 1988. Thermal Properties of Soils and Rocks. SGI Report No. 35, Linköping.

Watn, A., Gustavsson, H., Johanson, M., Forsman, J., Hagnestal, L. 2003. LWA geolight. LWA for Roads and Railways. Internordic Research and Development Project. Final Technical Report.. SINTEF STF22 F02154. Trondheim. 45 p.