Road in winter conditions: contribution of geotechnical and thermal properties

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ABSTRACT: With regard to road's freezing behaviour, effects of geotechnical and thermal parameters are generally well known. Previously, some effects on surface temperature had been studied. In this study, we present numerical simulations with Gel1D-LCPC and CESAR-LCPC software, to examine influence of other parameters on pavement surface temperature evolution. The parameters having the most importance are the water content and the meteorological conditions. The determination of these parameters is generally worse.

1 Introduction

The influence of the thermo-hydrous characteristics of the road layers already was largely studied. However, these studies had primarily related to the depths of freezing (Rouquès & Caniard, 1975 ; Corté et al., 1995) without being concerned with change of the surface temperature, knowledge essential for forecasts of the state of a roadway in the short time (Cames et al., 2000).

In this research, we continue our study to quantify the importance of various geotechnical and physical parameters of the road. The change of the temperature of surface during freezing period is observed for different atmosphere – pavement interface.

Numerical modelling estimates the precision with which these parameters must be known. We use Gel1D-LCPC and CESAR-LCPC software, while varying systematically all thermo-hydrous surfacing characteristics of the pavement. We present the results obtained for variation of thermal conductivity, water content of surfacing layer and variations of meteorological parameters: exchange coefficient and initial air and structure temperature.

2 Modes of transfer of energy to the surface of a pavement

The modes of transfer of energy (figure 1) to the surface of a pavement are carried out by:

- conduction in the structure
  $\phi = \lambda \, \Delta T$
- convection between the ambient air and the road surface
  $\phi = \alpha \, (T_{air} - T_s)$
- radiation of the surface
  $\phi = \sigma \, \varepsilon \, T_s^4$

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with ϕ : flux (W/ m K)
λ: thermal conductivity(W/ m K)
ΔT: thermal gradient (°C)
α: exchange coefficient (W/ m^2 °C)
T_{air}: temperature of air (°C)
T_s: temperature of surface (°C)
σ: Boltzmann constant (W /m^2 K^4)
ε: emissivity.

The atmospheric medium introduces an additional "mode of transfer", which is related to the changes of state of water on the road surface (L : latent heat of freezing).

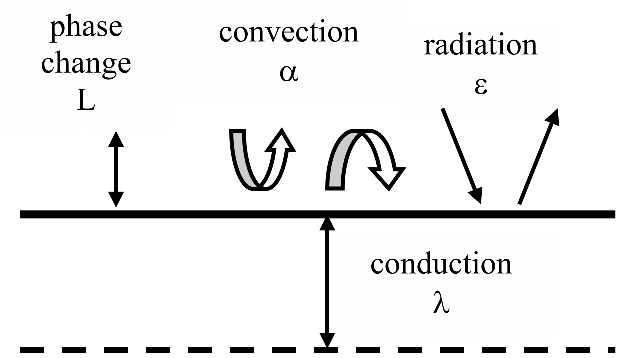

Figure 1. Modes of transfer of energy to the surface of a pavement.

3 Numerical study

3.1 Presentation of the pavement structure

The studied pavement has a classical configuration. It's composed of five different layers : an upper layer of draining bituminous concrete (DrBB, thickness : 3 cm), a 8 cm thick bituminous concrete binder (BBL), gravel on 22 cm, a treated flying ashes layer (25 cm), sifted red and black schist (100 cm) over natural ground. Their geometrical and thermal properties are well known (table 1). There are the reference values for the study.

Table 1: Pavement structure and geotechnical and thermal properties.

Pavement structure	Thickness (cm)	Dry density ρ (t/m^3)	Thermal conductivity (W/m.K)		Water content w (%)
			unfrozen λ_{ng}	frozen λ_g	
DrBB	3	1.96	1.10	1.10	0.0
BBL	8	2.35	2.00	2.10	1.0
Gravel	22	2.25	1.90	2.10	5.0
Treated flying ashes	25	1.35	0.60	0.93	14.0
Schist	100	1.80	1.40	1.52	12
Natural ground	-	1.70	2	2.80	25

3.2 Gel1D and CESAR-GELS software

Two programs, designed by the French “Laboratoire Central des Ponts et Chaussées (L.C.P.C.)”, was used in this study.

Gel1D-LCPC (Caniard et al, 1975) is a one-dimensional model for studying the evolution of the fields of temperature in a multi-layer one-dimensional solid mass. It determines the transfers resulting from the combined action of a variable flow imposed on the surface, initial thermal state of the ground as well as its physical characteristics, and water - ice phase change. The model takes the resolution of a coupled problem into account, whose unknown factors are fields of temperature and the propagation velocity of the frost front.

The boundary conditions can be of three different types, at each end of the solid mass: a condition of imposed temperature (Dirichlet), a condition of imposed flow (Neumann) and a condition of linear exchange (Fourier). We suppose known the initial temperature map of the solid mass of ground, with one or more lines of freezing. We can take also into account the radiation of the roadway, possibly associated with a condition of convectif exchange.

CESAR-GELS uses the finite element method, for a two- or three-dimensional problem. Considered heat exchanges are identical to those of Gel1D software. The carried out mesh makes it possible to take geometrical characteristics that Gel1D cannot distinguish into account.

3.3 Presentations of calculations

The one-dimensional model used for Gel1D is 14 m height about the road surface with a temperature of 14°C at the base. All layers are homogeneous.

With CESAR-GELS, the two-dimensional model is 2 meters height and 0.12 m width. The surfacing layer mesh is composed of gravel elements and others elements for modelling the influence of a thin film on the road surface (saturated or not). This simulates a water film filling roughness of surface. The others layers are homogeneous.

In this study, we show the influence of only some parameters on the evolution of the pavement surface temperature.

The fixed parameters in all calculations are the following:

- geometry of the pavement,
- thermo-physical properties for the lower layers,
- thermal flow on the lateral boundary,
- temperature at the base of the model.

The varying parameters are the following:

- thermal conductivity of the surfacing layer: +/- 20%,
- water content of the surfacing layer: 0, 1, 3, 6%,
- air temperature and initial structure temperature (0.5; 1 and 1.5°C),
- exchange coefficient α (for a low wind, $\alpha<10$ and for a strong wind, $\alpha>25$).

Influences of others parameters were before analysed, like the influence of saturation degree of the surfacing layer or the influence of intensity of the flux, … (De la Roque, 1997; Cames et al., 2000).

The studied scenario of air temperature corresponds at the end of the afternoon, when the solar radiation disappears, at the duration of the night, then at a few hours after the rising of the sun (like presented on figure 2). Air temperature decreases linearly from +1°C to –5°C in 12 hours then increases from –5°C to +1°C in also 12 hours.

4 Results and interpretation

We were interested in times necessary so that the road surface temperature reaches is +0.5°C, 0°C, -0.5°C, -1°C, -2°C, -3°C that we can respectively compared with corresponding time in the evolution of the air temperature. We also compared the various cases between them.

4.1 Influence of the geotechnical and thermal properties of the pavement structure

4.1.1 Influence of thermal conductivity of the surfacing layer

With Gel1D software, we consider that the upper layer of draining bituminous concrete is homogeneous, with a water content of 0%.

When conductivity increases, necessary time so that surface temperature reaches 0°C is longer (table 2). The difference between the times obtained for a conductivity λ_0 + 20% and a conductivity λ_0 - 20% is 29 minutes and 10 minutes for respectively $\alpha=6$ and $\alpha=30$. This is due to the greatest facility of restitution of the energy stored by the pavement (including geothermal flow).

These variations are not negligible, taking into account the times of intervention for treatment of ice, but the precision for the determination of the value of thermal conductivity that we currently have is already largely sufficient (about +/- 20%).

Table 2 : Influence of the thermal conductivity of the surfacing layer.

	$\alpha=6$		$\alpha=30$	
	time (h)	temp. (°C)	time (h)	temp. (°C)
$\lambda_{ng}=\lambda_g=$ 1.1 W/m.K	4:32	0.5	1:53	0.5
	7:13	0	3:19	0
	9:31	-0.5	4:37	-0.5
		-1	6:18	-1
		-2	9:13	-2
		-3	11:46	-3
$\lambda_{ng}=\lambda_g=$ 1.31 W/m.K (λ_0 + 20%)	4:42	0.5	1:57	0.5
	7:25	0	3:23	0
	10:10	-0.5	4:42	-0.5
		-1	6:31	-1
		-2	9:23	-2
		-3	11:54	-3
$\lambda_{ng}=\lambda_g=$ 0.89 W/m.K (λ_0 – 20%)	4:19	0.5	1:49	0.5
	6:56	0	3:13	0
	9:11	-0.5	4:31	-0.5
		-1	6:00	-1
		-2	8:59	-2
		-3	11:32	-3

4.1.2 Influence of the water content of the surfacing layer

To simulate the real behaviour of the upper layer of draining bituminous concrete during the winter (rain, snow, …), we realise a mesh with CESAR-GELS. This mesh allows us to take the roughness of pavement into account and to change the value of the water content. Voids between gravel may be filled by air (w=0%), air and water (w=3%) or only water (w=6%).

The influence of the water content is more significant when the surface temperature reach 0°C (figure 2).

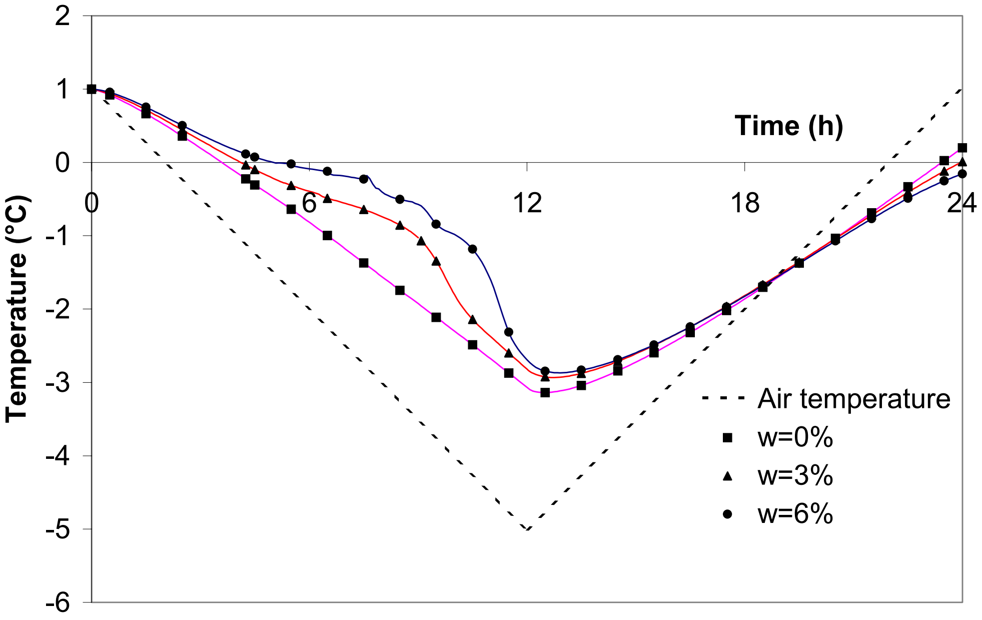

Figure 2: Results for different water content of the surfacing layer : 0, 3 and 6%

When we go down below 0°C, we observe a very strong influence of water content (table 3). Necessary time to the surface temperature to pass from 0°C to –0.5°C strongly varies: for α = 30, this time of passage is of 1:30 for w=0%, 2:30 for w=3% and 3:30 for w=6% (for α = 6, the temperature does not pass under –0.5°C pour w=3% and w=6%).

Table 3: Influence of the water content of the surfacing layer.

	Water content w=0%		w=3%		w=6%	
	time (h)	temp. (°C)	time (h)	temp. (°C)	time (h)	temp. (°C)
α=6	4:30	0.5	5:00	0.5	5:40	0.5
	7:42	0	8:45	0	11:15	0
	10:05	-0.5		-0.5		-0.5
		-1		-1		-1
α=30	2:00	0.5	2:15	0.5	2:30	0.5
	3:35	0	4:05	0	5:00	0
	5:05	-0.5	6:35	-0.5	8:30	-0.5
	6:30	-1	8:55	-1	10:05	-1
	9:10	-2	10:15	-2	11:17	-2
	11:50	-3		-3		-3

4.2 Influence of the meteorological conditions

In this part, we present the influence of two external parameters: the exchange coefficient and the initial temperature of the air on the pavement surface temperature evolution.

4.2.1 Influence of the exchange coefficient

The exchange coefficient α characterises the movement of air in contact with the road. For an episode without wind, its value is less than 10. On the other hand, a presence of wind is characterised by a value of α higher than 25 (up to 200 for a very powerful wind). Figure 3 represents the results obtained for two extreme values of α: 8 and 30. The used software is Gel1D.

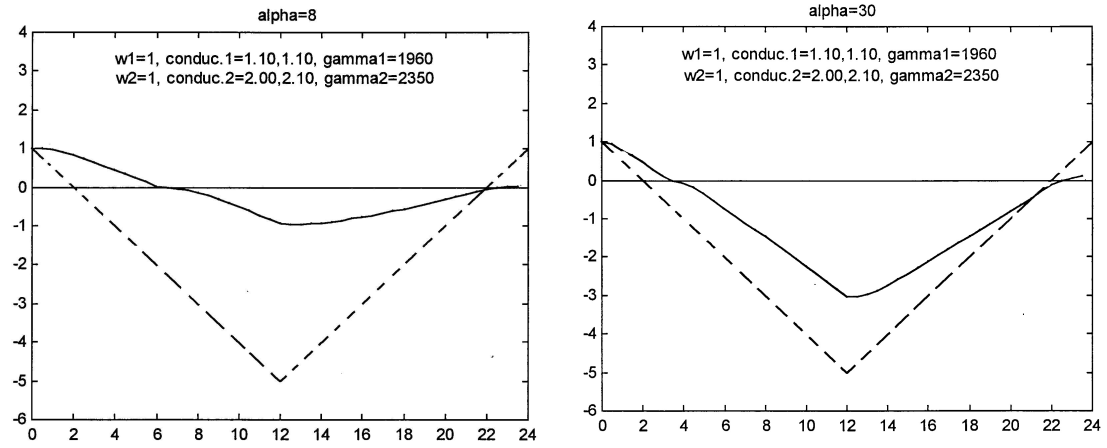

Figure 3. Two simulation results for $\alpha = 8$ and $\alpha = 30$

The value of exchange coefficient α is of primary importance on the results of calculations carried out. In the case of w=1%, for $\alpha=30$ (table 4), the road reaches a temperature of 0°C for a time of 3:20, whereas this time is of 6:09 for $\alpha=8$ (for $\alpha=18$, this time is 4:05.

Table 4 : Influence of the exchange coefficient

	Exchange coefficient					
	$\alpha=8$		$\alpha=18$		$\alpha=30$	
	time (h)	temp. (°C)	time (h)	temp. (°C)	time (h)	temp. (°C)
w=1%	3:49	0.5	2:25	0.5	1:54	0.5
	6:09	0	4:05	0	3:20	0
	10:00	-0.5	6:41	-0.5	5:24	-0.5
		-1	8:10	-1	6:40	-1
		-2	11:21	-2	9:24	-2
		-3		-3	11:52	-3
Minimal temperature		-0.96		-2.26		-3.07

Minimal obtained temperatures are –0.96°C and –3.07°C for respectively $\alpha=8$ and $\alpha=30$. This difference is very important for the development of ice on the road surface and its treatment.

This parameter has the most importance for well understanding and modelling the thermal cooling of a pavement.

4.2.2 Influence of initial temperature

Calculations were carried out with CESAR-GELS considering the upper layer water content equal to 3%. Two different initial air temperatures: +0.5°C and +1.5°C were simulated; the minimal temperature of air (-5°C) being always reached at the end of 12 hours.

The obtained results (figure 4) show very significant variations:

- for the initial temperature of 0.5°C, the road surface temperature reaches 0°C in 6:30 ($\alpha=6$) and 2:45 ($\alpha=30$),
- for the initial temperature of 1.5°C, these times are of 10:40 ($\alpha=6$) and 5:05 ($\alpha=30$).

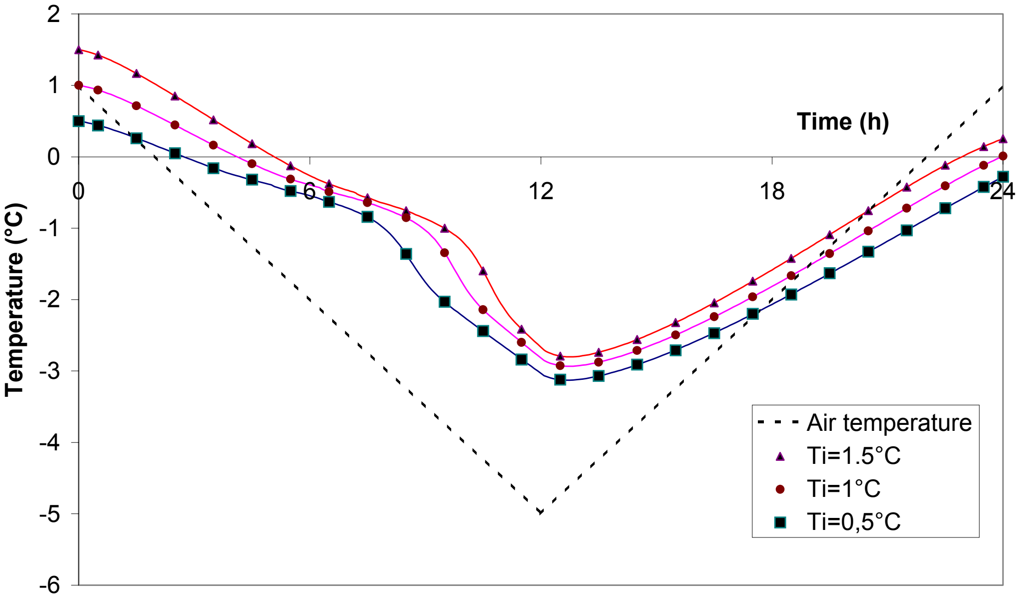

Figure 4: Results for different initial temperature values.

These differences in time are very significant (table 5): the quantities of energy stored in the road which require, to allow a cooling, a significant contribution of frigories. A good knowledge of the initial temperature of the air in direct contact with the pavement (few millimetres) is necessary.

Table 5 : Influence of initial temperature

	Initial temperature 0.5°C		1°C		1.5°C	
	time (h)	temp. (°C)	time (h)	temp. (°C)	time (h)	temp. (°C)
α=6	0:00	0.5	5:00	0.5	7:30	0.5
	6:30	0	8:45	0	10:40	0
		-0.5		-0.5		-0.5
		-1		-1		-1
α=30	0:00	0.5	2:15	0.5	3:33	0.5
	2:45	0	4:05	0	5:05	0
	5:40	-0.5	6:35	-0.5	7:10	-0.5
	7:55	-1	8:55	-1	9:30	-1
	9:25	-2	10:15	-2	10:55	-2
	11:55	-3		-3		-3

5 Conclusions

The numerical simulations carried out with Gel1D and CESAR-GELS software highlight some parameters having the most importance on the thermal behaviour of pavement, and in particular on the change of the surface temperature.

In this study, four parameters having a very particular importance are analysed:

- thermal conductivity of a homogeneous upper layer,
- water content of upper layer with roughness,
- exchange coefficient between air and road surface
- initial temperature of surface and air in contact.

The knowledge of these parameters is very important for the prediction of formation of ice on the road surface and its treatment.

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