THERMAL BEHAVIOR OF POROUS ASPHALT IN WINTER CONDITIONS

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ABSTRACT

The winter maintenance of open graded asphalt requires special measures, thus the Swiss Federal Roads Office has been concerned about the use of porous asphalt on bridges. By its open-textured structure this kind of pavement may retain snow and ice in its porosity and especially its thermal performance is noticeably different from that of the traditional dense asphalt structures. Thereby reservations were expressed regarding the installation of porous asphalt in regions with severe winter conditions and more especially on bridges in such regions.

In order to know the field of application of porous asphalt according to extreme winter conditions, in situ measurements were conducted and a modelling tool was developed. The measurements conducted on a porous asphalt highway section, including a concrete bridge with a porous asphalt surface, showed the evolution of surface temperatures in winter situations. They have allowed a first comparison between embankment and bridge from the observed weather events.

The conducted modelling was then used to evaluate the possible differences between porous and traditional asphalt installed on embankment and bridge, in order to assess the applicability of porous asphalt on bridges in winter conditions.

After the calibration of the model, conducted on the basis of measurements made between 2006 and 2008, it was possible to reconstruct remarkable events as: periods of extreme cold (hourly air temperature less than or equal to -10 °C), extended periods of cold (average daily air temperature less than 0 °C for at least 5 consecutive days) and periods of rapid change in temperature (difference of at least 10 °C between maximum and minimum of the air temperature over a period of 24 hours, with a minimum temperature less than or equal to -5 °C).

Based on the in situ monitoring, the modelling and the reconstruction of events, it was possible to develop recommendations for winter maintenance of porous asphalt on bridges.

KEYWORDS

POROUS ASPHALT / LOW TEMPERATURES / WINTER BEHAVIOUR

1. INTRODUCTION

Pavements layers materials show properties that are sensitive to temperature. Thus, in warm weather conditions viscoelastic bituminous mixtures lose their resistance to permanent deformation. In the other side, at temperatures close to zero degrees Celsius, pavement surface properties affect traffic security and particularly the grip resistance with the presence of snow and ice.

Porous asphalts, regarding their open structure, induce a higher operation risk by capturing snow and ice inside their cavities and showing a sensibly different thermal behaviour compared to dense materials. For this reason, some concerns have raised about the construction of porous asphalts in regions where the climate is considered as harsh in winter particularly when the pavement is laid over a bridge.

In order to investigate the application field of porous asphalt in extreme winter condition, measurements are collected from road sections and a simulation tool is developed.

Measurements are carried out on a motorway section comprising a bridge and covered entirely with porous asphalt. The data show the evolution of surface temperature during winter conditions and a comparison is drawn between bridge and embankment zones under selected particular climate events.

Furthermore, numerical simulations allowed the assessment of porous versus dense asphalt in either embankment or bridge situation. This permitted to investigate the applicability of porous wearing courses over bridges in winter conditions.

2. PAVEMENT TEMPERATURES

Many researches investigated temperatures profiles inside bituminous pavement layers with some comparisons between dense and open graded mixtures [3], [2].

Bäckström demonstrated thru an experimental study conducted in Sweden [1] that cooling of porous asphalt depends on ambient air temperature variation and that the freezing of the subgrade is related to the frost coefficient. He noted the better resistance to frost for pavement covered with porous asphalt compared to conventional mixtures because of the higher water content in the underneath soil increasing its latent heat.

In the framework of this research, many countries provided their appreciations on porous asphalt temperatures thru a questionnaire. In France, it was observed that surface temperature of porous asphalts is in average 1.6 °C lower than traditional materials with instant differences up to 5.5 °C during quick clouds dissipation. In Belgium, the difference between dense and porous mixtures is around 0.7 °C. In Japan, observations carried out during snow conditions demonstrated that porous asphalt surface is in average 0.2 °C colder than dense asphalt when the absolute temperature is higher than 1 °C.

For the present experience, measurements obtained from the test site indicate that surface temperature on the bridge is lower than the one of the embankment situation. The difference is 6.90% for the winter 2006/2007 and 6.25% for the winter 2005/2006.

The variation rate of temperature is another important indicator to assess according to climatic changes. Thus, it was observed in Belgium that during cooling, temperature sensors placed at the surface measure negative values approximately 34 to 40 minutes before those placed at surface of traditional pavements. During warming, porous asphalts show positive temperature 15 to 20 minutes before dense asphalts.

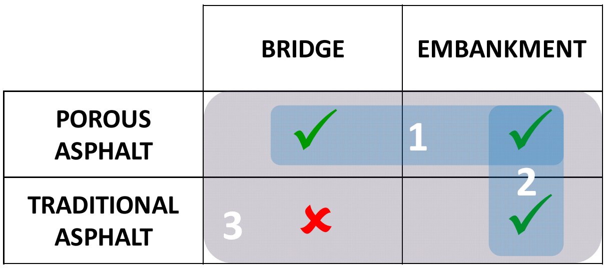
Winter thermal behaviour of porous asphalt is widely considered as an issue because of the low thermal inertia of concrete structures of bridges. Moreover, the pavement lacks the heat flux provided by the soil as for the embankment situation. Jean Livet from France produced several publications on porous asphalts behaviour under winter conditions. He demonstrated the need of modifying winter maintenance practice in the case of porous materials.

General studies on the thermal behaviour of porous asphalts in winter were conducted in Germany [6] and [7], Sweden [9] and [12], and France [10] as well as in Switzerland [11].

3. NUMERICAL SIMULATION

3.1. General methodology

Knowledge improvement is achieved by establishing situations typology thru the application of successive approaches. First, the relative behaviour of porous asphalt is assessed by comparing measurements collected from the embankment section versus the bridge section of the A5 motorway (link 1 of figure 1). Secondly, the replacement of traditional wearing course with porous asphalt is investigated thanks to field measurements collected from 1993 to 2006 on the A9 motorway in the Valais region (link 2 of figure 1). Remaining situations are analysed with numerical simulations (link 3 of figure 1).



	BRIDGE	EMBANKMENT
POROUS ASPHALT	✓	✓
TRADITIONAL ASPHALT	✗	✓

Figure 1 – Typology of relative behaviours

3.2. Thermal behaviour modelling

Simulation of thermal behaviour is achieved with COMSOL Multiphysics commercial software. This finite-element suite is suitable for solving different physical problems based on partial differential equations (PDE) such as heat transfer. The resolution of the PDE system with different boundary conditions is conducted thru a classical iterative procedure. To avoid numerical divergence of the solver, calculation steps are close enough to deal correctly with cases where climatic data show quick changes during particular weather events.

Simulation duration is 24 hours with a step of 10 minutes, which is the data acquisition rate in the field. Thus, in following charts, simulation time is comprised between 0 and 86400 seconds with a step of 600 seconds.

3.3. Structure size and geometry

A preliminary 2D-modelling of the embankment and bridge structures is done to evaluate the side effect of the problem. The aim is to verify the trueness of the hypothesis that a one-dimensional problem is sufficient for our needs. After some simplifications, 2D model comprised the following materials:

- Cement concrete for the bridge (bridge deck, longitudinal beam and parapet)
- Dense asphalt (70 mm thickness)
- Porous asphalt (50 mm thickness)

The geometry of both situations is constructed with a mesh composed of triangular elements with quadratic interpolation. Meshing is refined near the surface layer.

Comparison between 1D and 2D model demonstrated that 1D formulation is sufficient for short-term investigations with a particular focus on the pavement surface zone.

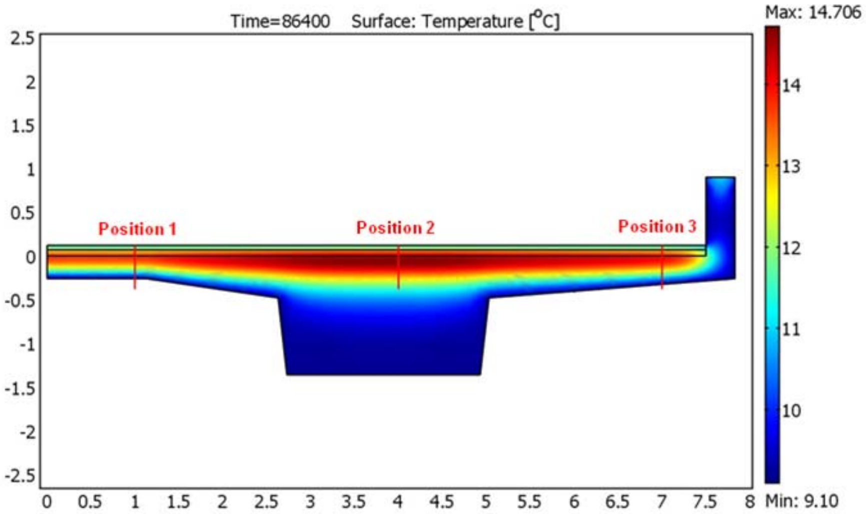


Figure 2 – Example of temperature distribution in the 2D-model of the bridge

3.4. Calibration approach

3.4.1. Model basis

The physical model is developed thru an iterative approach by determining progressively the different physical properties of the problem. The targeted model should be able to simulate adequately thermal behaviour of the structure under given climatic conditions. Starting with the simplest possible model, we introduce heat transfer phenomena according to their increasing complexity, i.e.: conduction, radiation and finally convection.

Conduction is governed by Fourier’s law, and is given for the 1D case by the following equation:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+Q=\rho C\frac{\partial T}{\partial t}$$

T is the temperature to be determined by solving the PDE regarding the position x and simulation time t, λ is material’s conductivity given in W/m/K, ρ and C are respectively the material’s density given in kg/m3 and the specific heat capacity given in J/kg/K. Q is the energy generated within the material in W/m3 and should be nil in our case.

The physical model is illustrated in figure 3 with the position of temperature sensors used for calibration.

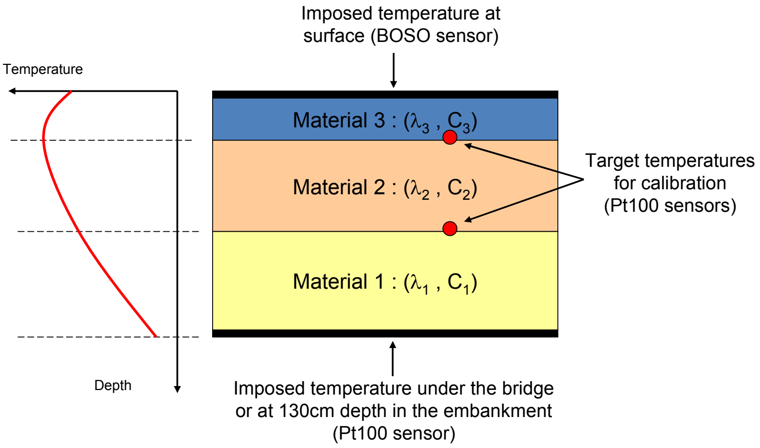


Figure 3 – Conduction calibration scheme

Net radiation at pavement surface is the balance result of the four radiation components: direct and reflected solar radiation, infrared radiation emitted by materials and finally infrared radiation reflected by clouds. All these radiations are collected thanks to two pyranometers and two pyrgeometers facing the pavement surface and the sky. Days with very low wind speed are retained for calibration to minimize convection effects. This is done by imposing measured temperatures on boundary condition and finding adequate conduction parameters to retrieve the recorded temperature distribution inside the pavement body.

The heat energy exchanged thru convection between pavement and air is given by Newton’s law:

$$Q = hS(T_S - T_\infty)$$

S is the exchange surface, T_S is surface temperature, T_∞ is fluid temperature (air). h is the heat transfer coefficient and is strongly related to wind speed. We selected in our case the formula proposer by Côté and Konrad:

$$h = 1.163 \cdot (4.84 + 3.36V_{wind}) \frac{294.16}{273.16 + T_{air}}$$

V_{wind} is wind velocity given in m/s, T_{air} is air temperature given in degrees Celsius.

3.4.2. Calibration procedure

The first calibration phase deals only with conduction by neglecting the wind effect. Thus, two quiet days are selected for this purpose, i.e. 9th and 28th of October 2006. Initial thermal gradient in the pavement body is given by field-collected data.

This first phase resulted in the determination of thermal properties of the three materials described above starting from seed value found in literature. The second step involves the introduction of both radiation and convection effects. Temperature evolution curves obtained from this phase show good concordance between simulated and measured data in both bridge and embankment situations.

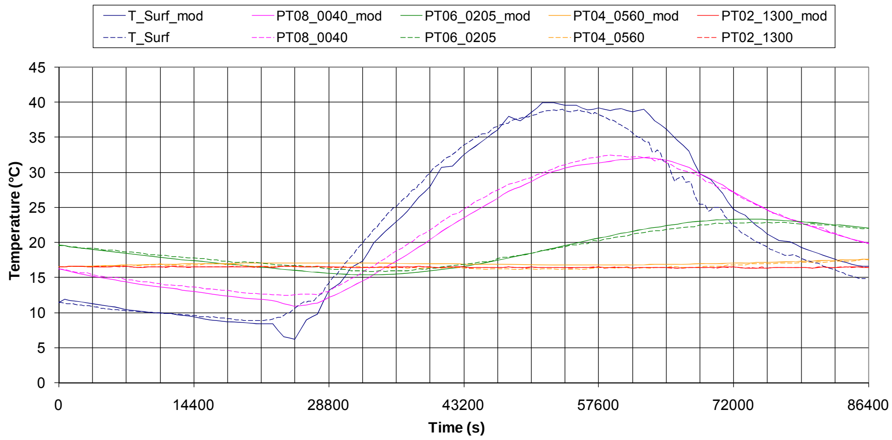


Figure 4 – Final calibration results for 3rd June 2006 in the embankment zone

The final step investigates winter conditions. Data corresponding to five days showing particular climatic events are retained for this final calibration phase. Distinction is made between bridge and embankment situations. Radiation is the field-measured one and the heat transfer coefficient is simplified as illustrated in Table 1.

Table 1 – Final model parameters after calibration

Structure	**Layer 3 (wearing course)**		**Layer 2 (base course)**		**Layer 1(concrete/ embankment)**		**Surface conditions**	
	λ **(W/m/K)**	C **(J/kg/K)**	λ **(W/m/K)**	C **(J/kg/K)**	λ **(W/m/K)**	C **(J/kg/K)**	**Radiation**	**Convection coef.**
Porous asph. / bridge	1.50	995	2.50	1086	1.80	933	Net radiation	$h = 3V_{wind}$
Porous asph. / embank.	1.50	995	2.50	1086	1.50	1120		$h = 3V_{wind} + 6$
Traditional asph. / bridge	2.50	1086	2.50	1086	1.80	933		$h = 3V_{wind}$
Traditional asph. / embank.	2.50	1086	2.50	1086	1.50	1120		$h = 3V_{wind} + 6$

4. EXPERIMENTAL SITE

The experimental site was selected because the test section is uncovered and includes a bridge over the Arnon River, and the availability of the motorway for instrumentation during the construction phase. Located at km 10.050 of the A5 motorway between Yverdon and Neuchâtel, the site was instrumented with different sensors in the pavement with a GSM automatic data transmission system. Temperature sensors were placed at different depths inside and outside the bridge as well as inside the embankment zone. Like most of the Swiss motorway bridges, BOSO and ARCTIS active sensors were placed at the surface of pavement by the Boschung Company to detect ice and warn winter maintenance center. A weather station is also installed beside the bridge and provides air temperature, dew point and rain or snow detection. The official weather station at Mathod, which is 10 km far from the test site, provides other weather parameters for the region.

The scheme of figure 5 illustrates the sensors placement inside the bridge structure and the embankment.

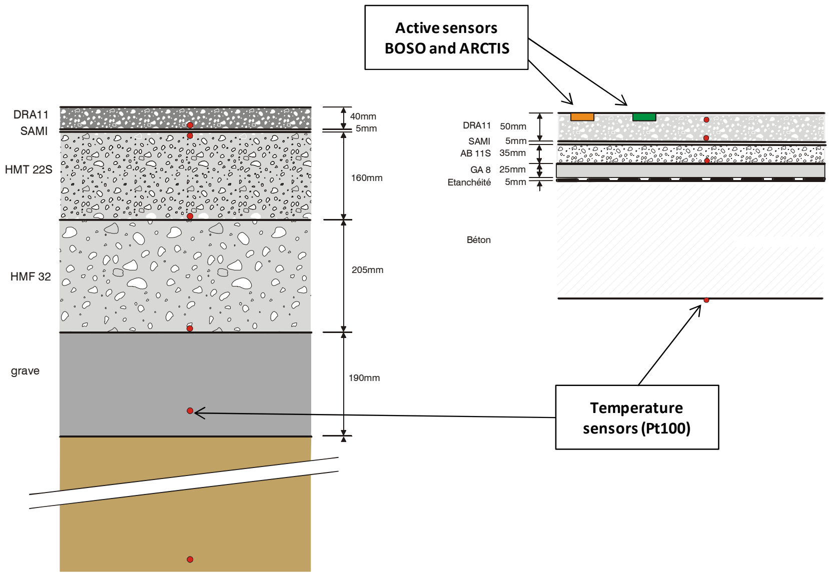


Figure 5 - Sensors' placement inside the embankment and the bridge

A 4-components Kipp & Zonen radiometer mounted on a traffic sign gantry is used to quantify direct and reflected radiations coming from pavement surface and the sky. Solar radiations are measured with two pyranometers with a wavelength range of 0.3 to 3 µm. Infrared radiations are measured with two pyrgeometers with a wavelength range of 5 to 42 µm. Pavement surface albedo, which is the ratio between reflected and incident radiation, could be directly calculated with available data.

5. MATERIALS PARAMETERS

Thermal properties of materials used in simulation are obtained from the calibration phase. Conduction parameters for unbound foundation layers are taken from Dysli publication [8]. Foundation material is a well-compacted limestone from Jura region with a conduction coefficient varying between 1.5 and 3.3 W/m/K and specific heat capacity varying between 850and 2200 J/kg/K. Simulation is achieved with a common value of 1.5 W/m/K for conduction coefficient and 1120 J/kg/K for specific heat capacity.

Convection coefficient value is refined for a better fit with field data and is thus given by the following formulae:
h = 3 x (Wind speed), for the bridge section,
h = 3 x (Wind speed) + 6, for the embankment section.

These simplified formulae are similar to Côté and Konrad's equation except the constant at origin that is nil for the bridge section.

6. EXPERIMENTAL DATA

Measurements collected during two winters provided, at the first sight, interesting average values for the winter period. Relevant parameters about thermal behaviour in winter condition are given in table 2.

It is also common and convenient to attribute a global value for the whole winter period. In our case, we selected the parameter of "winter harshness" or "risky hours" developed in the framework of previous researches carried out in our laboratory [4] and [5]. This parameter is the number of hours per winter where weather conditions permit the formation of ice, frost or snow over the pavement surface.

In the other hand, the winter maintenance center operates a warning system for the management of maintenance teams. This system is based on three levels of alarms A1, A2 and A3 which are described in table 2. Alarm A1 is a constraining warning condition that may occur during a long period. A2 and A3 alarms occur successively: The first one indicates that ice formation risk exists where as the second is issued when this effectively happens.

Table 2 – Definition of winter harshness and alarms

Alarm	**Description**	**Formula**
A1	Surface or air temperature below 0° C with wet pavement	Tsurf or Tair < 0 °C Surface state : not dry
A2	Difference between surface temperature and freezing point (TGT) lower or equal 2 °C: black ice risk	Tsurf – TGT ≤ 2 °C
A3	Surface temperature lower or equal freezing point (TGT): effective formation of black ice	Tsurf ≤ TGT
Snow	Snow detected	Precipitation = Snow
Winter harshness	Winter harshness is considered when one of following criteria is verified: 1. Air temperature is below 5 °C and rain or snow is detected 2. Air temperature is below 5 °C and relative air humidity is greater than 75%	1. Tair < 5 °C + Precipitation = Rain or Snow 2. Tair < 5 °C + RH > 75%

The three alarm levels show the efficiency of the detection system. During winter 2005/2006 (from 1.1.2006 to 30.4.2006), we count up 49 A1, 30 A2 and 12 A3 alarms during the 120 days period (i.e. occurrence ratios of 41, 25 and 10%).

7. ANALYSES AND COMPARISONS WITH SIMULATION

7.1. Comparison between traditional and porous pavements in the embankment zone

The comparison between traditional and porous asphalt over embankment is performed thanks to data collected from the measurement station located in Valais on the A9 motorway between 1993 and 2007. The traditional wearing course of the motorway was replaced with porous asphalt in 2002.

For each pavement structure (i.e. before and after 2002), characteristic periods are identified according to the following conditions:

- Period of extreme cold (FE): Hourly air temperature lower or equal -10 °C,
- Period of extended duration cold (FP): Average daily temperature below 0 °C during 5 consecutive days,
- Period of fast temperature variation (VT): Difference of at least 10° C between maximum and minimum air temperature over 24 hours; the minimal temperature should be below -5 °C.

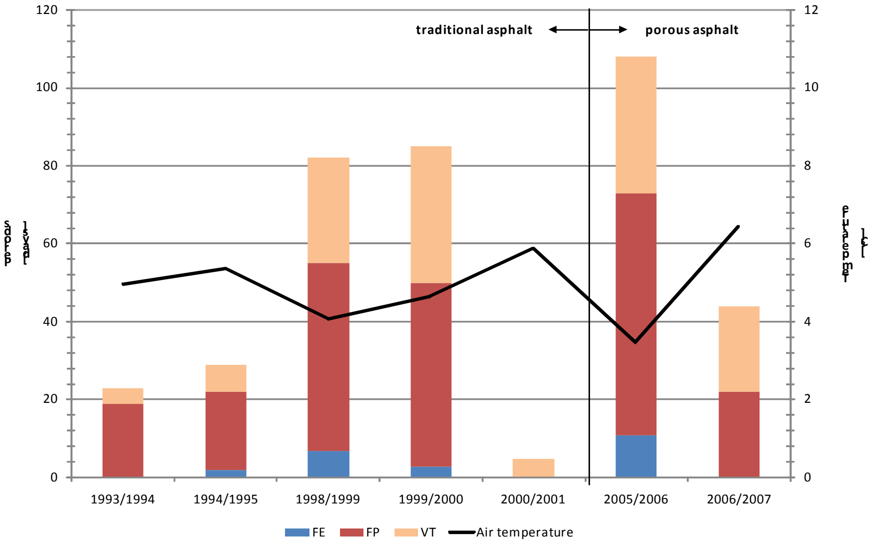


Figure 6 – Number of cold periods expressed as equivalent days

It is thus possible to perform the calibration as described previously on characteristic periods (FE), (FP) and (VT). The fit between measurements and simulations is acceptable and sufficient to retain simulated curves.

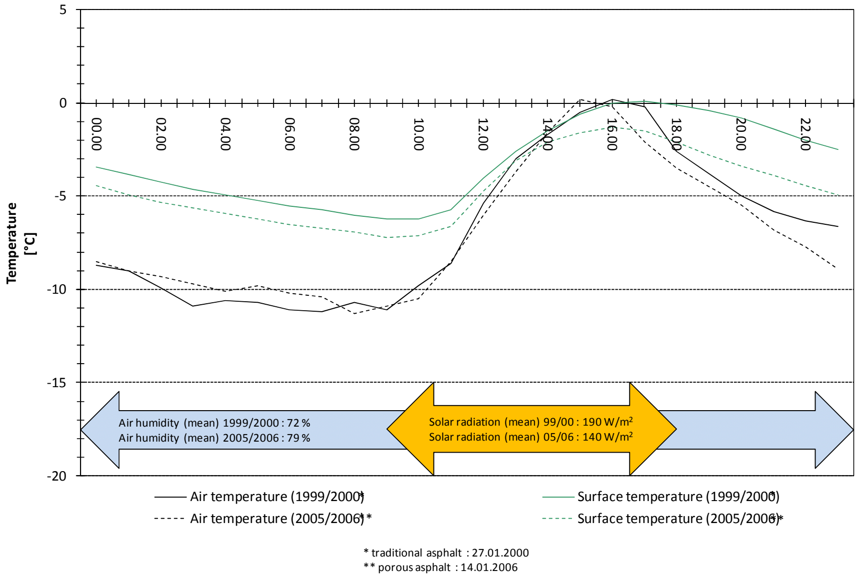


Figure 7 – Periods with comparable extreme cold before (27.01.2000) and after (14.01.2006) porous asphalt construction

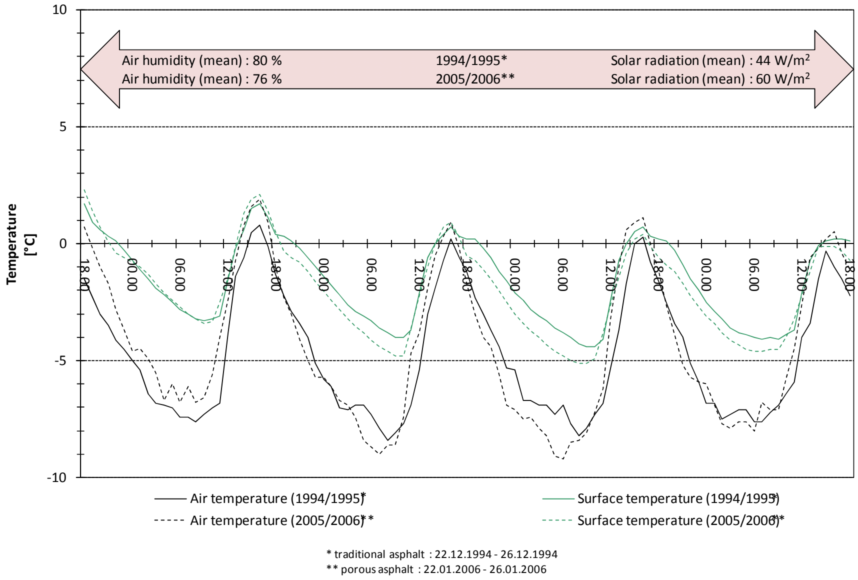


Figure 8 – Periods with comparable extended duration cold before (22 to 26.12.1994) and after (22 to 26.01.2006) porous asphalt construction

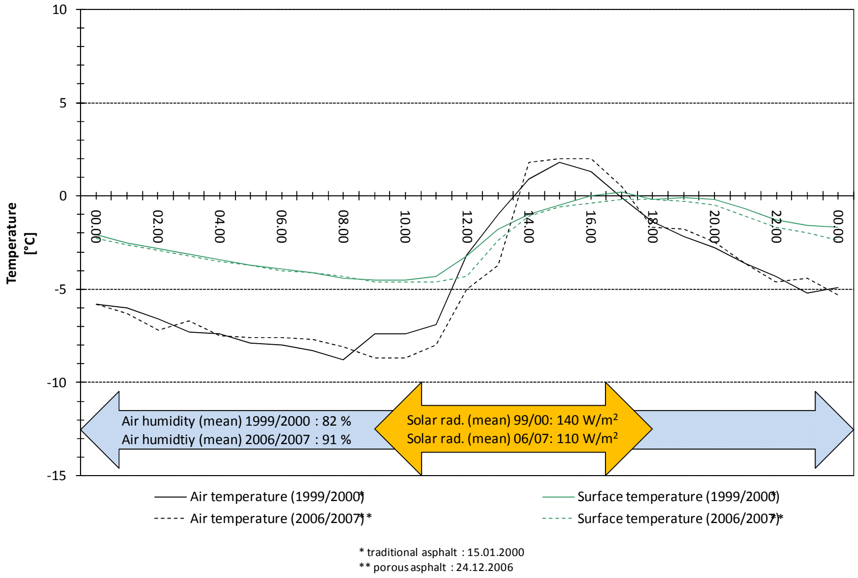


Figure 9 – Periods of comparable fast temperature variation before (15.01.2000) and after (24.12.2006) porous asphalt construction

7.2. Effect of porous asphalt on a bridge during winter conditions

Simulation model allowed the reconstitution of 4 events considered as representative of risky winter behaviours. It is then possible to assess and compare the 4 situations described in section 3.1, namely: porous or traditional asphalt on the bridge or the embankment zones.

The most pertinent results provided by simulation are the rates of cooling and warming of pavement surface, as well as the duration where the surface temperature is below 0 °C. It is also interesting to analyze the intervention time defined as the time interval for the surface temperature to decrease from 2 °C to 0 °C.

Table 3 – Temperature decrease rates of pavement surface in degrees/hour

Date	Air	Porous/Bridge	Porous/Embank.	Trad./Bridge	Trad./Embank.
30.jan.2007	-2.9	-4.0	-3.5	-2.6	-2.6
10.dec.2006	-3.3	-3.9	-3.5	-2.4	-2.4
12.dec.2006	-3.6	-3.3	-3.2	-2.3	-2.4

Table 4 – Temperature increase rates of pavement surface in degrees/hour

Date	Air	Porous/Bridge	Porous/Embank.	Trad./Bridge	Trad./Embank.
30.jan.2007	2.0	3.1	2.4	2.2	1.9
10.dec.2006	2.9	4.2	3.6	3.2	2.7
02.jan.2007	2.4	7.4	6.4	5.1	4.8
12.dec.2006	1.8	4.5	4.0	3.2	2.9

Table 5 – Duration in minutes for surface temperatures below 0 °C

Date	Air	Porous/Bridge	Porous/Embank.	Trad./Bridge	Trad./Embank.
30.jan.2007	600	750	680	560	560
12.dec.2006	282	650	330	440	130

Table 6 – Duration in minutes for a cooling from 2 to 0 ° C

Date	Porous/Bridge	Porous/Embank.	Trad./Bridge	Trad./Embank.
30.jan.2007	146	156	336	286
12.dec.2006	218	428	418	618

8. CONCLUSIONS

Particular climatic events are selected and simulated on existing and non-available pavement structures. General observations about surface temperature are drawn:

Whatever is the wearing course material (porous or traditional asphalt) surface temperature in bridge sections is always lower than surface temperature in embankment sections when air temperature is close or below 0°C.

On the bridge, and in the case of fast cooling of the pavement, porous asphalt surface is up to 2° C colder than tradition asphalt surface.

Temperature variation slope of porous asphalt is more important during cooling or warming of pavement. Porous asphalt cools and heats faster compared to traditional asphalt.

Simulation of extreme cases gives similar results to those observed for real situations with temperature differences between porous/traditional less important (approx. 1 to 2 °C).

It was not noted a different winter behaviour which clearly distinguishes the porous and traditional asphalt situations. Under certain conditions, one or the other can evolve to a winter risk. Moreover, the difference between bridge and embankment situations is also noted with porous asphalt, without being quantitatively more important.

Bridge remains more sensitive to weather conditions than embankment, but porous asphalt does not worsen this issue.

The present comparison show different behaviours depending on the observed case, particularly that:

- porous asphalts are more sensitive to air temperature variations, this induces higher cooling and warming rates.
- during cold periods (air temperature below 0 °C), surface temperatures are lower on the bridge than on the embankment. This is true for both porous and traditional asphalts.
- during specific situations with strong wind and long duration cold, surface temperature are similar for porous and traditional asphalt whatever is the pavement situation (bridge or embankment).

– critical weather conditions such as the combination of low wind, uncovered sky, no solar radiation and quick drop of air temperature induce a high risk behaviour for porous asphalt as well as for traditional asphalt.

Finally, this study demonstrates that winter behaviour of porous asphalt constructed over bridge sections is not considerably risky compared to dense asphalt. However winter maintenance approach should be adapted.

Further applications for the model could be foreseen, as the simulation of water freeze inside porous asphalt, as well as temperature distribution in pavement materials for the purpose of moduli back-calculation.

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