Development of a predictive model for the temperature distribution in a flexible pavement based on measurements of a monitored road section.

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ABSTRACT

The elastic modulus of an asphalt concrete pavement is strongly influenced by the temperature of the layer. This is due to the rheological behaviour of the binder present in asphalt concrete layer. For this reason it has a great importance knowing the thermal state of the layer for comparing the values of the elastic modulus of pavements in different climatic conditions. In the case of deflection measurements this is especially necessary. Basing on these considerations, a predictive model of the temperatures inside the pavement has been developed. It uses as input the temperature at the surface as is recorded during FWD tests. The model is founded on a database of temperatures measured at surface and at different depths (10, 15, 20, 30 cm) of an asphalt concrete pavement during three years.

Keywords: pavement, temperature, FWD, thermal state

1. INTRODUCTION

In the evaluation of the conditions of a road pavement, the temperature at which this is, plays a central role. Moreover, that temperature varies in the superficial layers for the effects of the climatic conditions. Further, in most cases the superficial layers are made of asphalt concrete, which possesses a mechanical behaviour strongly dependent on temperature.

It is possible to study the mechanical behaviour of a asphalt concrete with experimental tests at different temperatures. If you wish to characterize *in situ* the behaviour of a asphalt concrete with deflectometric measurements, the temperature can not be generally measured in a direct way except by drillings inside the pavement. This involves too long times with respect of the FDW tests.

To avoid the direct measurement of the temperature inside the pavement, it is also possible to employ some predictive models, which simply require the value of the temperature in the most external layer of the pavement. They are based on the temperature diffusion law in a half space in a transient state.

The ASTM D4695 (Standard Guide for General Pavement Deflection Measurements) gives indications concerning the procedure for the temperature survey during a FDW test.

2. CONTENTS OF ASTM D4695

As anticipated, the knowledge of the temperature distribution inside a pavement is fundamental. This is particularly true when you wish to evaluate the mechanical characteristics of a bituminous mix; in that case it is essential to known the temperature at which each value is referred.

FDW is a widespread non-destructive *in situ* test for the study of the mechanical properties of a pavement. It is possible to give a mechanical characterization of the pavement layers through the interpretation of the deflection basin generated by the FDW. It is evident that the deflection basin and the interpretation itself are influenced by the temperature of each layer, so requiring specific and appropriate methods to estimate the temperature inside the pavement.

If you need of particularly accurate values, the ASTM D4695 suggests the use of drillings and to position the instruments for the temperature measurement inside. It is quite obvious that the proposed approach has not a general practicability especially in the case of extensive areas. Alternatively, the cited ASTM D4695 suggests to obtain the temperature measurements in the surface during a period of five days and then to utilize these values as surface temperature wave for the calculation of the temperature at different depths; no indications are given concerning the type of provisional model to apply and the interval of time between two measures.

During a FWD test, there is also the possibility to measure the air and the surface temperature in addition to the deflection basin. These data are important because they identify in a punctual manner the value of the temperature where the test has been done.

Nevertheless, at the same time they are inefficient for two reasons. First, they can not be used in the definition of surface temperature wave, where the values referred to several days are necessary (details in Section 3); this is in contrast with the fact that usually FWD measurements are taken during the night (with the aim of not obstacling the traffic) and for few hours at time. Second, these measures could be referred to points far away from each other some kilometres, as a consequence they could be at different climatic conditions. For all these reasons, with the exclusive use of a FWD test is not possible to retrieve all the necessary data for a exhaustive description of the course of the temperature in surface.

3. CALCULATION MODEL

To improve the approach for the determination of the temperature distribution, we report the results obtain with the use of a thermometer station of monitoring placed in highway A1 (north direction) near Settebagni – Fiano (in Roma). Further, basing of these results we propose a method to determine the temperature distribution inside a pavement at the instant of a FWD test.

If it is possible to measure the temperature at the surface for a certain interval of time with a fix thermometric station, these values can be employ to retrieve the temperature in depth.

To this aim, it is convenient to provide one or more fix thermometric station; they should be opportunely located according to the place where the measurement will be conducted. If, for instance, it will be in an airport, a single fix thermometric station can be utilized; this because there will be not a big climatic difference between two different points of the airport. Instead, for measurements along a road path, it is more convenient to situate more than one station to be able to reveal differences in temperature between two points.

The law of diffusion in a alph-space in transient state is a tool to determine the temperature distribution at different dephts. In particular Thomlinson's equation is applied to calculate the temperatures inside a paviment; it supposes that the temperature distribution inside and at the surface of the pavement is sinusoidal:

$$Tp(z) = Tsg + To \cdot e^{-\left(\frac{z}{\sqrt{d}} \cdot \sqrt{\frac{\pi}{t_c}}\right)} \cdot \sin\left(\frac{2\pi}{t_c} \cdot t - \frac{z}{\sqrt{d}} \cdot \sqrt{\frac{\pi}{t_c}}\right) = Tsg + Toe^{-(z \cdot \beta)} \cdot \sin\left(\frac{2\pi}{t_c} \cdot t - z \cdot \beta\right) \qquad (1)$$

where:

$Tp(z) =$ temperature at the depth z [°C]

$Tsg =$ surface mean temperature during the day [°C]

$To =$ amplitude of the temperature cycle at the surface [°C]

$z =$ distance from the surface [cm]

$d =$ thermal diffusion of the medium (usually is function of temperature) [cm^2/sec]

$t_c =$ period of one cycle [sec]

$t =$ time [hours]

In most cases the surface temperature wave has not a sinusoidal form; for this reason, to apply this approach it is necessary to approximate the measured performance with a sum of harmonic functions. The temperature distribution is so calculated applying the Equation (1) to the single harmonics and then summing over the different contributions.

Further, it should be noticed that considering a surface temperature wave referred to a single day, as indicated by ASTM, is not advisable, because it could provide not precise results. As a consequence, we suggest the following methodology.

The main idea is similar to De Baker's approach for the determination of the temperature distribution inside a pavement. He distinguishes two parts: the first takes account of the cyclic variation of the temperature during a year, the second of the daily variation. The temperature at a certain instance results as the superposition of the two functions.

Our method considers a longer cycle (n days) beside the daily cycle. The temperature value at different depth is calculated using Thomlinson's diffusion equation, summing over the effect of two surface temperature waves (one day and n days functions). The introduction of a second series (referred to n days), as explained later on, is justified by the fact that the thermal inertia plays a great role. Before applying the diffusion equation, it is necessary knowing the signal of the surface temperature wave of interest. As anticipated, it is essential to use a sinusoidal signal or the sum of signals of this type. The initial measurements have been approximated by a Fourier's series.

$$T_{\sup}(t) = c_0 + \sum_{i=1}^{4}\left(c_i \cos(i\bar{\bar{t}}) + d_i \sin(i\bar{\bar{t}})\right) + \sum_{i=1}^{4}\left(a_i \cos(i\bar{t}) + b_i \sin(i\bar{t})\right) \tag{2}$$

Dove:

$$\bar{t} = (t \cdot 2\pi)/86400 \qquad con \;\; t[\text{sec}] \tag{3}$$

$$\bar{\bar{t}} = (t \cdot 2\pi)/(86400 \cdot n) \qquad con \;\; t[\text{sec}] \tag{4}$$

n = number of days of the second period

Figure 1 illustrates the principle on which the proposed methodology is based on.

The behaviour of the superficial temperature (red curve) during a period of *n* days is divided into two parts, one referred to a single day and one to a period of *n* days (blue curves).

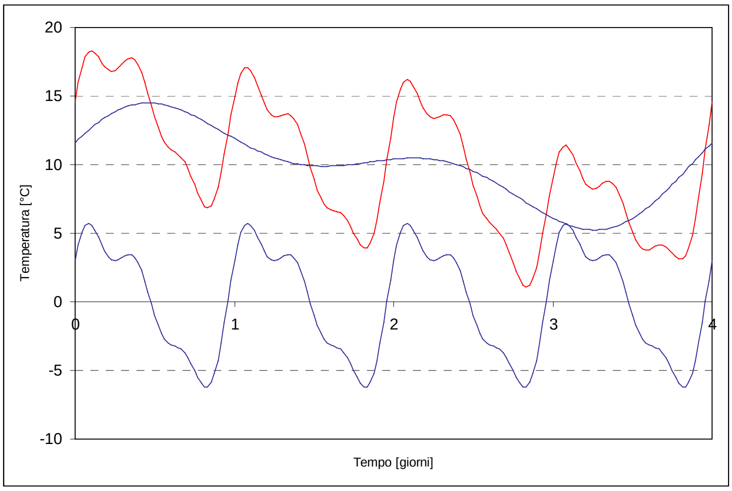

Figure 1 – Example of superface temperature wave for n days

4. COLLECTION OF THE EXPERIMENTAL DATA

The collection of the experimental data has been performed in place Settebagni along highway A1 (Rome), previous authorization for the installation of the instruments given by Società Autostrade.

The installation took place at the end of the 90s, and could be possible thanks to the use of some funds (PRIN project) to investigate the problems related to the maintenance of the existing roads. In this context a system for monitoring the temperature distribution inside a pavement has been realized.

The thermometric monitoring station consists of different equipments that enable the measurements and the acquisition of the thermal data: a pyrometer for the values of the superficial temperature, a thermometer for the air temperature, an hygrometer for the air humidity and a irradiation monitoring system. These are outside the pavement. Some devices for the measure of the temperature (thermoresistor) are placed inside the pavement at different depths (10,15,20,30 cm).

The pavement under study is a composite: a layer of asphalt concrete (35 cm height) directly layed on a concrete slab (25 cm); this is over the unbond layers of pavement. In *Figure 2* we have a picture of a core and the layout of the thermoresistors as function of the depth.

Two cores have been extracted, for positioning the thermoresistors. Then they have been replaced and closed with bitumen.

Figure 2 – Example of core

The monitoring system enabled to acquire the value of all the described quantities at interval of 30 minutes for the period 2001-2006.

5. VALIDATION OF THE PROPOSED MODEL

In order to know the optimal length of the superficial temperature measurement for the use as input in the model , we compared the results obtained with the proposed methodology when it is applied to three different periods of measurement (1,3,5 days) and different depths (10, 15, 20, 25, 30cm)

For the analysis only the measures of a specific year (2003) have been considered. For each month, two days have been analyzed (the first and the 15th), taking into account of three cases (1,3,5 days).

In the first case, the surface temperature wave has a period of one day that coincides with the analyzed day. For the remaining cases, the surface temperature way has been obtained considering the value of the superficial temperature of 3 and 5 days and choosing as last day the day in which the temperature has been calculated. In this way it could be possible evaluate the influence, in terms of precision, of the use of long acquisition periods.

In all three cases the surface temperature wave has been approximated with a Fourier's series. The so obtained surface temperature wave has been implemented in Thomlison's diffusion equation for the calculation of the temperature distribution.

The matching between the experimental and calculated temperature distributions at different heights has been reached with a minimization of the root mean squares based on the diffusivity.

The approach has been applied to all analyzed days. In this way we have obtained a value of diffusivity for each of the analyzed case (see table below).

	1 day	RMS	3 days	RMS	5 days	RMS
january	0.0058	5.25	0.0067	1.51	0.0041	1.63
february	0.0074	2.76	0.0044	2.84	0.0040	2.70
march	0.0054	2.41	0.0022	1.66	0.0017	1.72
april	0.0070	2.73	0.0041	2.45	0.0040	2.53
may	0.0052	4.13	0.0041	3.11	0.0058	3.05
june	0.0059	2.75	0.0038	2.48	0.0062	2.61
july	0.0058	5.18	0.0035	3.91	0.0054	3.94
august	0.0083	4.44	0.0048	4.90	0.0039	4.91
september	0.0055	8.46	0.0038	4.46	0.0025	3.90
october	0.0069	3.70	0.0047	3.23	0.0098	3.30
november	0.0065	4.53	0.0041	3.46	0.0106	3.71
december	0.0076	3.59	0.0049	3.89	0.0112	3.79

Table 1 – Value of diffusivity at every month

Nevertheless, in practice the values of temperature at different depths are not available for the calculation of the diffusivity (you know the diffusivity itself). The table is intended to suggest a value of diffusivity for the calculation of the temperature in depth.

We compared the results obtained from the predicted temperature distribution in the three selected periods with the experimental data in order to find the optimal period. The parameter choose for the evaluation of the best surface temperature wave is the root mean square. In the following table we reported the maxima and the minima root mean squares referred to the analyzed days of the year.

	1 day	3 days	5 days
RMS min	2.41	1.51	1.63
RMS med	4.16	3.16	3.12
RMS max	8.46	4.90	4.91

Table 2 – Value of RMS of three cases

It appears manifest a substantial difference among the values if a single day of acquisition is take; this difference decreases if the days of acquisition are three or five.

As a consequence, it is sufficient to take into account three consecutive days; more is not justified from an economical point of view.

As example, we reported here the case of a single day (31/03/03) of acquisition in the three different situations.

5.1.1 Length of the measurement of the superficial temperature: 1day

In this case, starting from the measured values of the superficial temperature a Fourier's series based only on the daily course is employed.

In the following picture the behaviour of the surface temperature wave and the temperature distribution (as obtained from Eq. (6) for the surface temperature wave) are illustrated.

$$T_{\sup}(t) = a_0 + \sum_{i=1}^{4}\left(a_i \cos(i\bar{t}) + b_i \sin(i\bar{t})\right) = 13.65 - 2.32\cos\bar{t} - 1.80\sin\bar{t} +$$

$$+1.42\cos 2\bar{t} + 0.38\sin 2\bar{t} - 1.14\cos 3\bar{t} - 0.83\sin 3\bar{t} + 0.39\cos 4\bar{t} - 0.11\sin 4\bar{t} \qquad (5)$$

where:

$$\bar{t} = (t \cdot 2\pi)/86400 \qquad con \;\; t[\mathrm{sec}] \qquad (6)$$

From the picture, you can notice that a certain difference between calculated and experimental data exists. From Thomlinson's law, for z -> ∞, the temperature value approximates the mean superficial value. In our case the mean superficial value is of about 14°C, while at the depth of 30cm the value is of the order of 10°C. The difference is probably due the thermal inertia of the pavement, that absorb heat from the underlied layers, being at a lower temperature.

Considering the importance of the temperature in the evaluation of the mechanical behaviour for bituminous mixes, it seems evident that the use of a single day of acquisition is not a choice of accurateness.

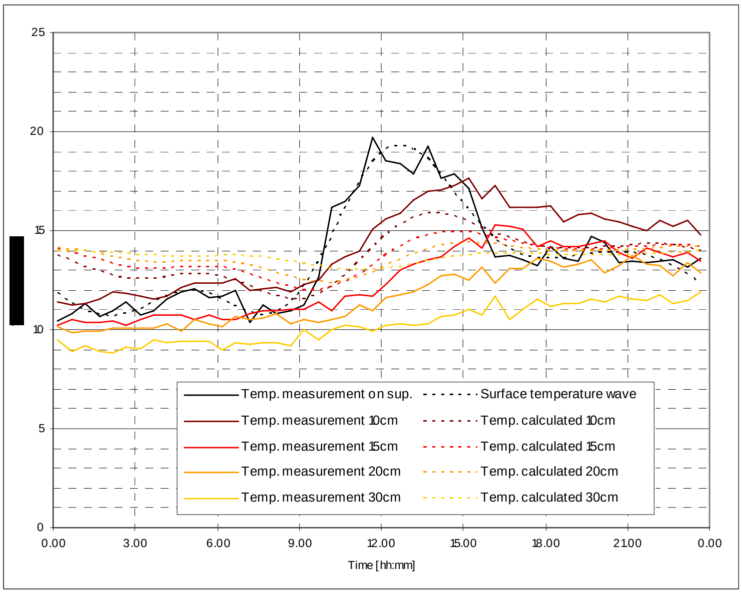

Figure 3 – Comparison between measured and calculated temperatures

5.1.2 Length of the measurement of the superficial temperature: 3 days

In this case the surface temperature wave has been retrieved from the minimization of the root mean square between the measurements referred to three consecutive days of acquisition and the Eq.(2) applied to a three days cycle.

In the figure (4) the course of the temperature at different depths during a period of three days is reported. The data for the last day, which is the object of our analysis, are enlarged in the figure(5), with the aim of comparing easily the answers of the model in function of the depth.

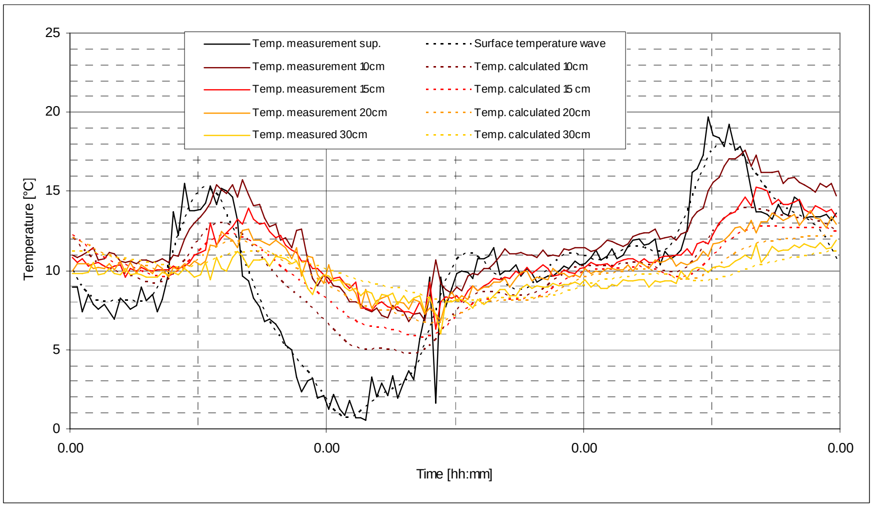

Figure 4 – Course of the temperature during a period of three consecutive days

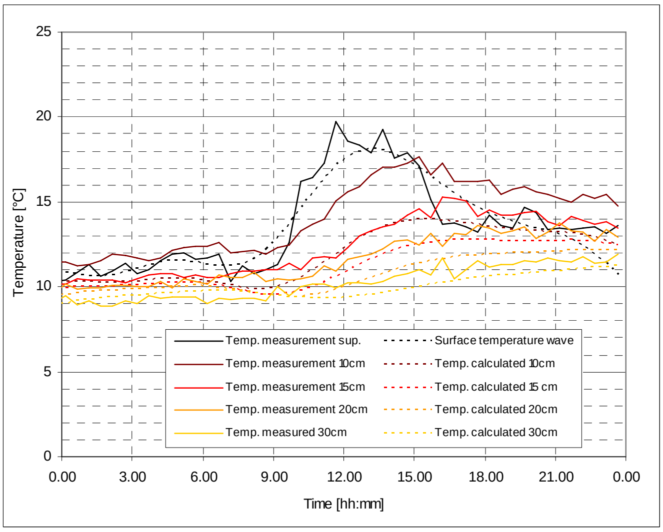

Figure 5 – Course of the temperature during the last one day

If we compare the data referred to one day or three days of acquisition, it is clear that the gap between experimental and calculated value is much lower in the case of a longer period of acquisition.

In that situation (days from 1/1/03 to 3/1/03) we used the following expression to characterize the surface temperature wave:

$$T_{\text{sup}}(t) = 9.78 + 3.24\cos\bar{\bar{t}} - 3.37\sin\bar{\bar{t}} + 0.66\cos 2\bar{\bar{t}} + 0.95\sin 2\bar{\bar{t}} + \\ + 0.06\cos 4\bar{\bar{t}} - 0.96\sin 4\bar{\bar{t}} - 2.83\cos\bar{t} - 2.00\sin\bar{t} + 1.09\cos 2\bar{t} + \\ + 0.41\sin 2\bar{t} - 0.49\cos 3\bar{t} - 0.49\sin 3\bar{t} + 0.11\cos 4\bar{t} - 0.15\sin 4\bar{t} \qquad (7)$$

5.1.3 Length of the measurement of the superficial temperature: 5 days

Finally, we reported here the results obtained using a surface temperature wave calculated on a basis of five consecutive days.

In the figure (6) the course of the temperature at different depths during a period of five consecutive days is reported. The data for the day of interest are enlarged in the figure (7), with the aim of facilitate the comparison of the answers of the model in function of the depth.

In this case the surface temperature wave has been characterized by the following expression:

$$T_{\text{sup}}(t) = 9.59 + 1.75\cos\bar{\bar{t}} + 0.54\sin\bar{\bar{t}} - 0.23\cos 2\bar{\bar{t}} - 2.58\sin 2\bar{\bar{t}} + \\ - 1.96\cos 4\bar{\bar{t}} - 0.73\sin 4\bar{\bar{t}} - 2.83\cos\bar{t} - 2.00\sin\bar{t} + 1.09\cos 2\bar{t} + \\ + 0.41\sin 2\bar{t} - 0.49\cos 3\bar{t} - 0.49\sin 3\bar{t} + 0.11\cos 4\bar{t} - 0.15\sin 4\bar{t} \qquad (8)$$

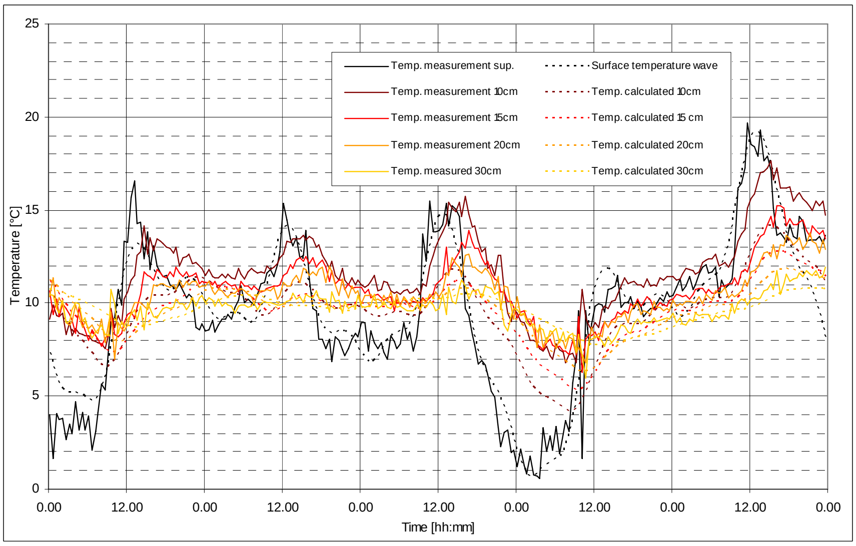

Figure 6 – Course of the temperature during a period of three consecutive days

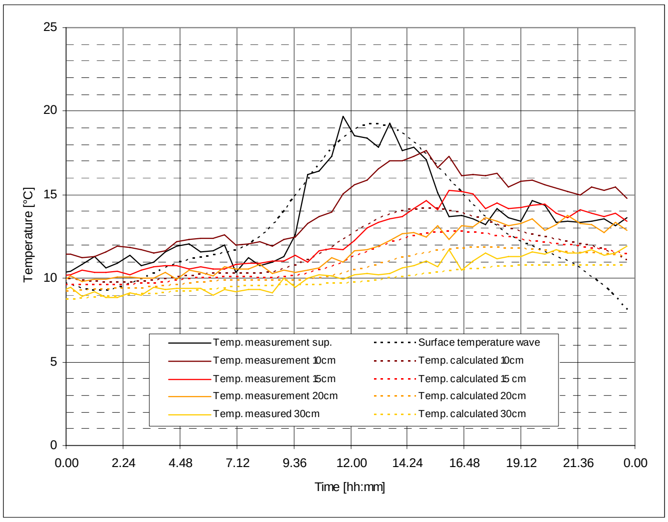

Figure 7 – Course of the temperature during the last one day

6. APPLICATION OF THE PROPOSED MODEL IN THE CASE OF DEFLECTOMETRIC MEASUREMENTS

The measures of temperature obtained with a FWD cover a length of time that is shorter the optimal one (3 days, as we demonstrated before). Consequently, it is necessary to make use of one or more fixed thermometric monitoring stations. It is known that, for different reasons, it could be or not a variable gap between the values surveyed by a FWD or a fixed thermometric monitoring station. When this gap exists, we suggest the following approach.

Where a FWD is placed, it should be considered as superficial temperature of the pavement the value obtained by the FWD and not by the fixed thermometric monitoring station at the instant of the test. Then, for the same point, the temperature at 60 cm of depth (level for which it is possible to assume that the temperature is not influenced by the daily changes of the superficial temperature) should be calculated employing the proposed model and utilizing for the surface temperature wave the data measured by the fixed thermometric monitoring station. For depths between 0 and 60 cm, we suggest to scale the curve of the temperature distribution got with the theoretical model by the subsequent proportion:

$$T_{adj}(z) = \frac{(60-z)\cdot\left(T_{FWD} - T_{0\,Fou}\right)}{60} + T_{z\,Tho} \qquad (9)$$

dove:

$T_{adj}(z)$ = scaled temperature at depth z [°C]

z = depth [cm]

T_{FWD} = superficial temperature obtained by a FWD [°C]

$T_{0\ Fou}$ = superficial temperature obtained using the measurements done by a fixed thermometric monitoring station [°C]

$T_{z\ Tho}$ = temperature at depth a obtained using Thomlinson's law [°C]

In this way, the error committed at the surface is distributed over an height of 60cm.

An example of correction of the distribution curve calculated with the model is illustrated in the following picture. It was assumed the temperature measured by a FWD is lower of 4°C with respect of the value obtained using the measurements done by the fixed thermometric monitoring station.

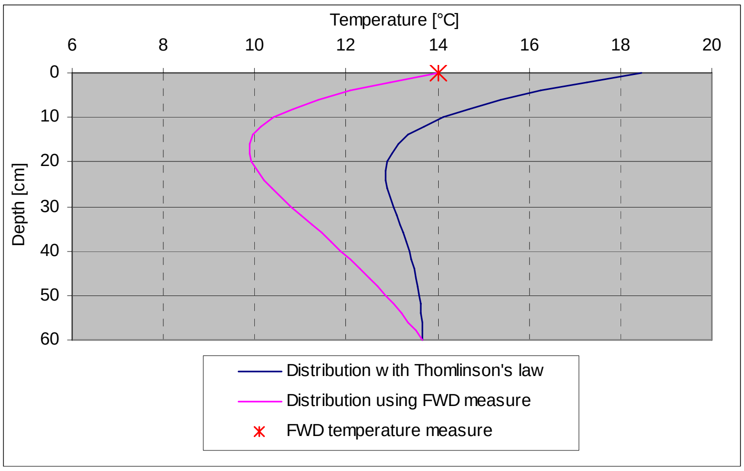

Figure 8 – Temperature distribution as function of the depth from the surface

At the end, it has to be clarified the limits and the range of acceptability of the approximation. We distinguish three situations.

First, if the FWD measure is in agreement with the measure obtained using a fixed thermometric monitoring station, you can use this second surface temperature wave to calculate the distribution temperature. Second, if the difference is not so large, it is possible to apply the proposed approximation. Third, if the gap is quite large, the approximation can not be consider valid.

It is necessary to give a quantitative indication of the limits of application of the proposed approximation and estimate the implications of a certain error in the calculation of the temperature.

To compare moduli of bituminous mixes calculated at different temperatures several correlations have been proposed. Witczak's equation has the form:

$$\begin{aligned}\log E_{ac} &= 5{,}553833 + 0{,}028829 \cdot \left(\frac{P_{200}}{f^{0{,}17033}}\right) - 0{,}03476 \cdot \mathrm{V_V} + 0{,}070377 \cdot \eta + \\ &+ 0{,}000005 \cdot \mathrm{t_p}^{1{,}3+0{,}49825\log f} \cdot \mathrm{P_{ac}^{0{,}5}} - \frac{0{,}00189}{f^{1{,}1}} \cdot \mathrm{t_p}^{1{,}3+0{,}49825\log f} \cdot \mathrm{P_{ac}^{0{,}5}} + 0{,}931757 \cdot \left(\frac{1}{f^{0{,}02774}}\right)\end{aligned} \tag{10}$$

A sensitivity analysis on temperature has been performed in order to investigate the influence, on the modulus calculation, of an error in the evaluation of the temperature.

In the following table we give a selection of the errors committed in the calculation of the elastic modulus of a bituminous mix when it is introduced an error in the evaluation of temperature inside the mix itself.

error / temp.	-6	-4	-2	+2	+4	+6
10°C	30%	20%	10%	-10%	-19%	-28%
20°C	44%	28%	14%	-13%	-24%	-34%
30°C	58%	37%	17%	-15%	-29%	-40%

Table 3 – Percentage error of moduli as function of the temperature

From the table it is possible to point out some considerations. The percentage error in the evaluation of the elastic modulus is not proportional to the error on the temperature, which changes at the variation of the temperature. A small error on the temperature leads to a sensible error on the elastic modulus.

As a consequence, we can not assign a unique value of acceptance to the error because it is a function of the temperature of interest (so varying with the temperature).

7. CONCLUSIONS

In this paper we present a predictive model for the calculation of the temperature distribution during a FWD test. This approach requires the acquisition of the superficial temperatures by one or more fixed thermometric monitoring stations. It was pointed out that the matching between the quality of the prevision and the time needed for the test is achieved for a period of three days.

On the basis of available experimental measurements, this methodology enables to get errors of the root mean square lower than 4,90.

Further, in the practice a difference between the value of the superficial temperature obtained by FWD or using fixed thermometric monitoring stations is possible; for this reason we also presented the application of the proposed model to this specific situation. Its limitations and the ranges of applicability requires further appropriated experimental studies.

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