Evaluation of the concept of equivalent temperature for pavement design

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ABSTRACT: Because of the thermal susceptibility of bituminous materials, the levels of stress, strain, and damage in bituminous pavements are strongly dependent on temperature. As taking into account temperature variations in design of bituminous pavements is difficult, design is performed, in France, for a constant temperature, called the equivalent temperature θ_{eq}.
θ_{eq} is defined as the mean temperature leading to the same fatigue damage of the pavement as the real temperature variations. The calculation of θ_{eq} requires knowing the variation of modulus and fatigue properties of bituminous materials with temperature. If such results are generally available for the modulus, it is seldom the case for fatigue properties. For this reason, in practice, a constant equivalent temperature of 15 °C is assumed for design.
This paper presents a study carried out to determine real values of θ_{eq}, for different pavements and climatic conditions, using real measurements of temperature and traffic on experimental pavements, and experimental values of fatigue properties at different temperatures. The results indicate significant variations of θ_{eq} with climate and material properties. The effect of these variations on pavement design is discussed.

KEY WORDS: Pavement design, climate, temperature, fatigue, thermal susceptibility.

1 INTRODUCTION

This study is part of a research project conducted to improve the French pavement design method, for bituminous pavements. In this method, the main design criterion for bituminous layers is a fatigue criterion. The objective of the work is to evaluate how temperature variations (e.g. real climatic conditions) affect the fatigue design life. After defining the notion of equivalent temperature θ_{eq} used in the French pavement design method, the paper presents experimental results on the thermal susceptibility of fatigue characteristics of French bituminous materials. Then, these results, and temperature measurements from real pavements are used to determine the equivalent temperature θ_{eq} for these pavements, and their design life. The influence of material properties, pavement structure, traffic and climate on θ_{eq} is discussed.

2 THERMAL SUSCEPTIBILITY OF FATIGUE PROPERTIES OF BITUMINOUS MIXES

In the French pavement design method, the design criterion for bituminous layers is a fatigue criterion, based on the results of laboratory, strain-controlled, 2 point bending fatigue tests. For pavement design, the fatigue law is expressed by the following simplified relationship:

$$\varepsilon = \varepsilon_6 \cdot \left[N/10^6\right]^b \tag{1}$$

Where: ε is the strain level at failure, N is the number of load cycles.
ε_6 and b are 2 parameters; ε_6 represents the strain level leading to failure for 10^6 load cycles.

For pavement design, fatigue properties are determined for only one level of temperature (10 °C) and one frequency (generally 25 Hz). However, various experimental studies (Domec et al., 2005, Lundström et al., 2004) indicate that fatigue properties of bituminous mixes, like complex modulus, depend on temperature and frequency.

Figure 1 summarizes results from several studies on the influence of temperature on the fatigue behaviour of French bituminous materials (Moutier, 1991, Domec et al., 2005, De la Roche et al. 1997). The tests have been performed for temperature ranging form -10 to 30 °C, and similar frequencies (25 Hz or 40 Hz, which does not lead to significant differences). On this figure, the variations of the fatigue parameter ε_6 with temperature are normalized by the values of ε_6 at 10 °C. The results obtained for the five materials are similar: the fatigue resistance first decreases when the temperature increases, reaches a minimum for temperatures varying between about 0 and 15 °C, and then increases again. The paper examines the consequences of these variations of fatigue properties on design life.

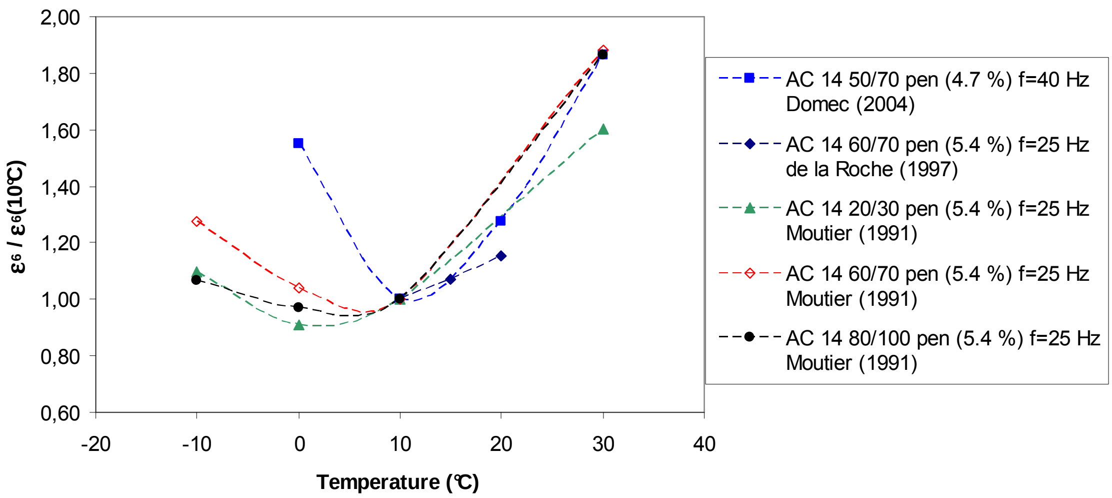

Figure 1: Experimental variations of the fatigue parameter $\varepsilon_6(\theta)/\varepsilon_6(10°C)$ with temperature.

3 NOTION OF EQUIVALENT TEMPERATURE

3.1 Principles of the French Pavement Design Method

The French pavement design method (SETRA, LCPC, 1994) is a mechanistic design method, based on a multilayer linear elastic model. The main input parameters are the traffic, the climatic conditions (temperature, frost, moisture conditions), the mechanical properties of the materials, and the risk of failure. For bituminous pavements, the design is based on 2 criteria:

- A rutting criterion, limiting the maximum vertical strain at the top of the unbound granular layers and of the subgrade.
- A fatigue criterion, limiting the maximum tensile strain ε_t at the bottom of the bituminous layers, expressed as follows :

$$\varepsilon_t \leq \varepsilon_6(\theta_{eq}, f) \cdot \left[NE/10^6\right]^b \cdot k_r \cdot k_s \cdot k_c \qquad (2)$$

With: ε_6 the strain leading to a fatigue failure for 10^6 cycles, determined at a temperature θ_{eq} and a frequency *f* representative of traffic loading. *b*: the slope of the fatigue line, *NE* the number of equivalent standard axle loads (130 kN dual wheel axle loads), *kr*, *ks* and *kc* are coefficients related respectively with the risk of failure, the bearing capacity of the soil and the calibration of the model.

The fatigue parameter ε_6 depends, in theory, on temperature and frequency. However, in practice, it is determined at 10 °C and 25 Hz only. Then, for pavement design calculations, two assumptions are made: the influence of frequency on ε_6 is neglected (design calculations are performed at 10 Hz); the variation of ε_6 with temperature is assumed to verify the following simplified relationship, for any temperature θ:

$$\varepsilon_6(\theta) \cdot (E(\theta))^{0,5} = constant \qquad (3)$$

Where $E(\theta)$ is the complex modulus. Relationship (3) is a simplification, and its validity will be discussed in this work.

3.2 Calculation of the Equivalent Temperature

Pavements are subject to temperature variations, which have a considerable influence on the behaviour of bituminous mixes. These temperature changes lead to variations of fatigue resistance, but also to such phenomena as thermal cracking, and wheelpath rutting at high temperatures. The concept of "equivalent temperature", θ_{eq}, used in the French pavement design method is related only with fatigue damage. θ_{eq} is defined as the constant temperature leading, for a given pavement, to the same fatigue damage as the real variations of temperature in the pavement. θ_{eq} can be theoretically calculated, knowing the temperature variations and the traffic, and using the notion of fatigue damage, and Miner's law. For a given temperature θ_i, and a number of standard axle loads (ESALs) $n_i(\theta_i)$ passing at θ_i, the corresponding fatigue damage is:

$$D(\theta_i) = \frac{n_i(\theta_i)}{N_i(\theta_i)} \qquad (4)$$

Where $N_i(\theta_i)$ is the number of ESALs leading to fatigue failure for the temperature θ_i. Then, the definition of the equivalent temperature θ_{eq} leads to the following relationship:

$$\sum_i \frac{n_i(\theta_i)}{N_i(\theta_i)} = \frac{\sum_i n_i(\theta_i)}{N(\theta_{eq})} \qquad (5)$$

Where $N(\theta_{eq})$ is the number of loads leading to failure for θ_{eq}.
Introducing the expression of the fatigue law in equation (5) leads to the expression of the elementary damage (for 1 load application) for temperature θ_{eq} ,

$$d\left(\theta_{eq}\right)=\frac{1}{N\left(\theta_{eq}\right)}=\frac{1}{\sum_i n_i\left(\theta_i\right)}\left[\sum_i n_i\left(\theta_i\right)\left(\frac{\varepsilon_6\left(\theta_i\right)}{\varepsilon\left(\theta_i\right)}\right)^{1/b}\times 10^{-6}\right] \quad (6)$$

Where: $\varepsilon(\theta_i)$ is the tensile strain at the bottom of the bituminous layer under the standard axle load and $\varepsilon_6(\theta_i)$ the strain leading to a fatigue failure for 10^6 cycles (for temperature θ_i)

Knowing the annual distribution of temperatures in the pavement, and the variations of ε_6 with temperature, it is also possible to establish a curve of evolution of the elementary damage in the pavement with temperature, defined by:

$$d\left(\theta_i\right)=\left[\frac{\varepsilon_6\left(\theta_i\right)}{\varepsilon\left(\theta_i\right)}\right]^{1/b}\times 10^{-6} \quad (7)$$

The equivalent temperature θ_{eq} is the temperature corresponding to the damage $1/N\left(\theta_{eq}\right)$.

In principle, for a given pavement, a specific equivalent temperature can be calculated, as defined above. However, in practice, the data required (traffic, temperature variations, temperature susceptibility of fatigue properties) are seldom available. For this reason, for pavement design, an equivalent temperature of 15°C is generally assumed in France, independently of the material properties and local climatic conditions.

3.3 French Climatic Conditions

The map presented on figure 2 presents values of the mean annual temperature in France (for the period 1951-1980), and gives an idea of thermal contrasts over the French territory. The mean annual temperatures range from 8°C to 16°C, from the North East to the South of France. These differences put in question the possibility to use a single equivalent temperature θ_{eq} (presently 15 °C) for pavement design. For this reason, one of the objectives of this work is to try to evaluate the range of variation of θ_{eq}, for different French climatic regions.

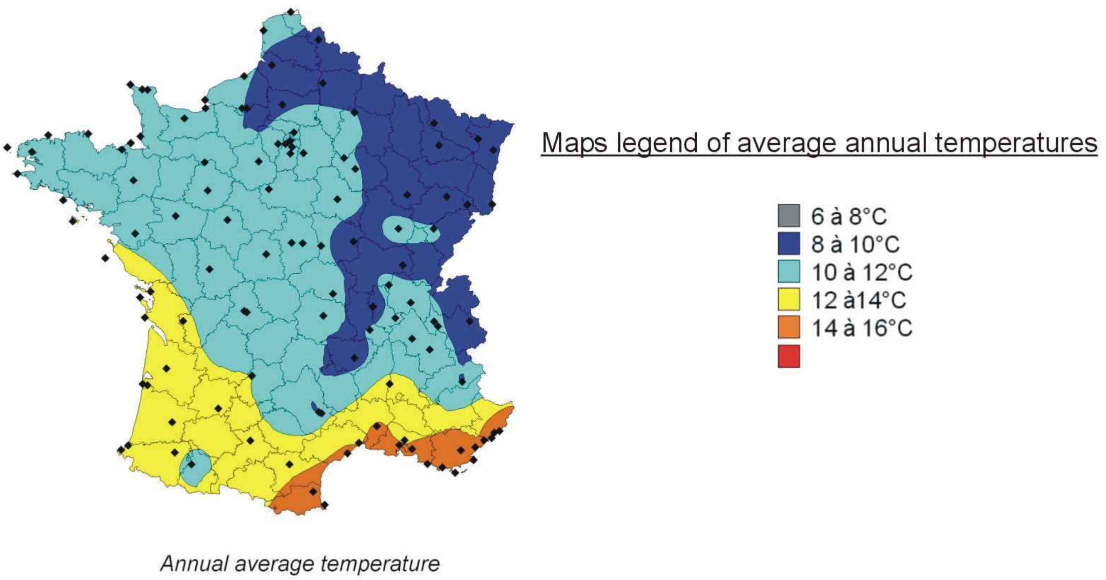

Figure 2: Map of mean annual temperatures in France

4 EQUIVALENT TEMPERATURE CALCULATIONS FOR THREE EXPERIMENTAL SITES

One difficulty of the study was to find pavements where continuous temperature measurements were available, for long periods. Three such experimental pavements have been found: A composite pavement (bituminous base, cement-treated subbase), located in the Vosges (North-East of France), a flexible, low traffic pavement from Charente (South-West of France), and a thick bituminous pavement from Loire-Atlantique (West of France). Traffic measurements were not available for the 3 experimental pavements, and so it was decided to make simulations using traffic data coming from several counting stations, located on different roads, representative of various levels of traffic.

4.1 Traffic Data

A network of 40 traffic counting stations exists on the French network of national roads. These stations record axle loads, speeds and vehicle types. For this study, it was decided to select data from 7 stations, presenting complete data, and different levels of traffic (between 250 and 5000 heavy vehicles per day). As the objective was mainly to have data representative of various traffic conditions, only one year of traffic, 2005, was considered.

Figure 3a presents the mean daily traffic distributions, defined by the relative percentage of heavy vehicles passing each hour, for the 7 selected counting stations. The levels of traffic vary largely during the day (90 % of the traffic passes between 6a.m. and 10 p.m.), but the general shape of the traffic distributions (in percentage) is very similar for all the stations.

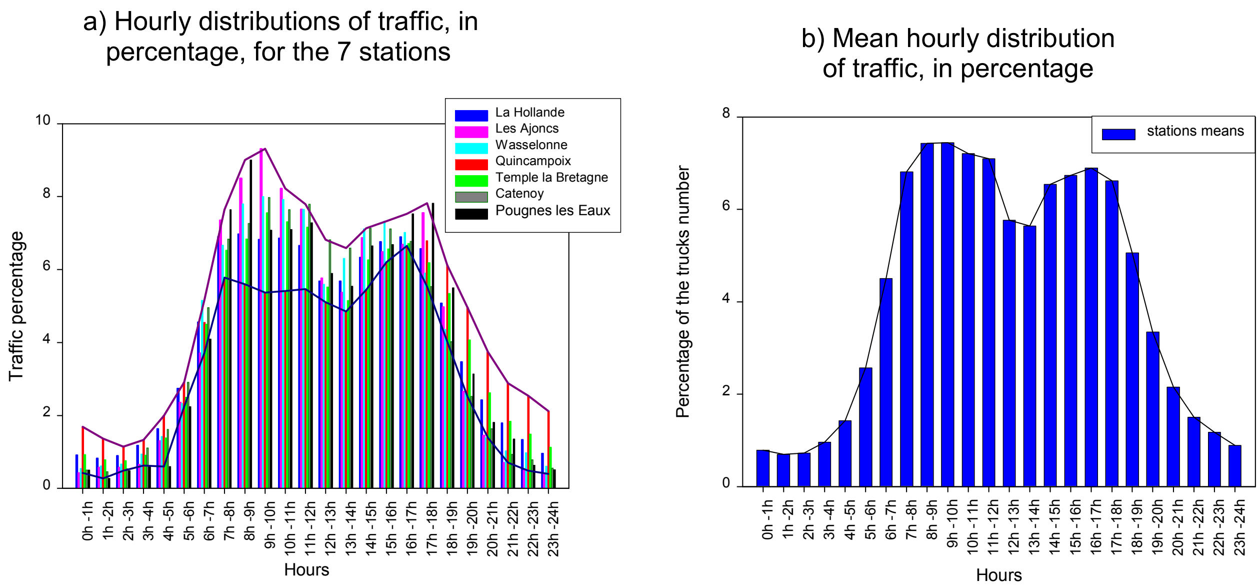

Figure 3: mean daily distributions of traffic, in percentage, for the different counting stations

Equivalent temperatures θ_{eq} have been first calculated separately for each traffic station. However as the traffic distributions are comparable, very similar results have been obtained for the 7 traffic stations (differences of less than 1 °C on θ_{eq}). For this reason, it was decided to consider, for the rest of the study, only one “reference” traffic distribution, corresponding to the mean of the distributions from the 7 stations (see figure 3b).

4.2 Temperature Data

Temperature measurements have been made on the 3 experimental pavements at several depths, over periods of one year or more, at intervals of one hour maximum. For each site, a period of measurement of one year, giving reliable measurements was retained for the modelling: The year 2002 for the Charente site, 2008 for Loire-Atlantique, and 2005 for the Vosges. Figure 4 presents histograms of annual temperature distributions, in percentage, for the 3 sites, at a depth of 15 cm. It can be noted that the Vosges site is colder than the two others, with temperatures lower than 4°C during approximately 28 % of the year. The two other sites have more similar temperature distributions.

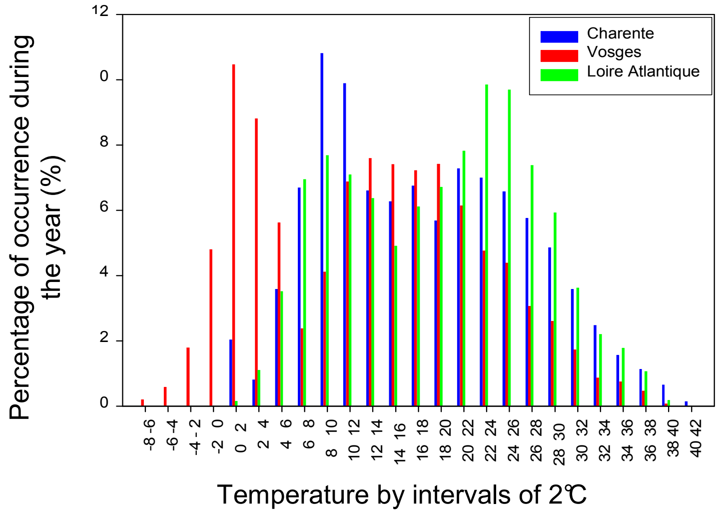

Figure 4: Histogram of annual temperature distributions for the 3 experimental sites

4.3 Equivalent Temperature Calculation Methodology

The procedure for the calculation of the equivalent temperature, and of the damage in bituminous pavements, has been implemented in the pavement design software Alizé LCPC (2005). The calculations are performed using time steps of one hour for the temperature variations. The traffic is converted in number of ESALs. The procedure is the following :

- The pavement structure is defined and the temperature in the middle of each pavement layer is calculated, using the available temperature data, at time intervals of one hour.
- ALIZE is used to calculate, for each hour, the tensile strain ε_t at the bottom of the bituminous layers, with values of elastic modulus function of the temperature.
- The elementary fatigue damage is then calculated for each hour, using values of ε_6 function of temperature (using one of the experimental laws of figure 1).
- Finally, Miner’s law is applied to calculate the cumulated damage for each hour and then for the whole design life of the pavement. The equivalent temperature is then determined, as explained in 3.2.

Figure 5 shows examples of calculated curves of variation of elementary damage with temperature, for a reference pavement, (8 cm thick wearing course, 16 cm thick road base).

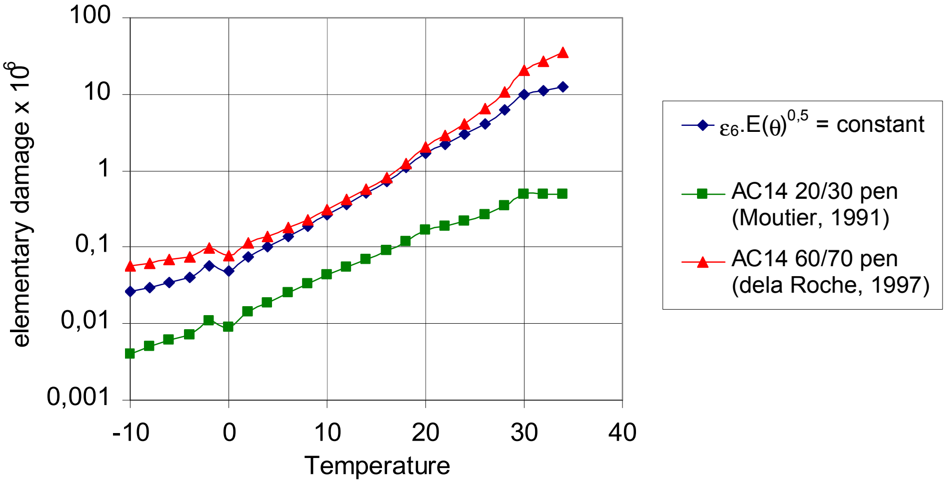

Figure 5: Examples of curves of variation of elementary damage with temperature obtained with different laws of variation of the fatigue parameter ε_6.

The results of figure 5 show that the elementary fatigue damage increases when pavement temperature increases, but that the results are very dependent on the law of variation of ε_6 (simplified law adopted in the design method, or experimental law).

4.4 Equivalent Temperature Calculation Results: reference case

At first, the equivalent temperature has been calculated for the following "reference" case:

- Pavement structure : 8 cm thick asphalt concrete (AC) wearing course, two 8 cm thick road base asphalt (RBA) layers, soil modulus of 120 MPa.
- Variation of the modulus of the bituminous materials (wearing course and base course) described using standard modulus values available in the ALIZE software. (This software provides a database of typical material characteristics, for standard French materials).
- Thermal susceptibility of ε_6 defined by the simplified law $\varepsilon_6(\theta)\cdot(E(\theta))^{0,5} = cons\tan t$.
- Traffic distribution corresponding to the mean of the 7 traffic stations (figure 3b).

Table 1 presents the equivalent temperature values obtained for this reference case, with the temperature data from the 3 experimental sites. The results indicate differences of more than 3°C between the values of θ_{eq} obtained for the 3 sites (West and North East of France) and a maximum difference of about 6°C with the value of 15°C usually adopted for design.

Table 1 : Equivalent temperatures calculated for 3sites, for the reference case

	2002-Charente	2005-Vosges	2008-Loire-Atlantique
θ_{eq}	20.5 °C	17.7 °C	21.1 °C

These results have been obtained with limited data, and are not representative of the diversity of French climatic conditions. However, they show that considering a constant value of equivalent temperature in France is not very realistic. It can be noted that the differences obtained for the 3 sites are of the same order as the differences between the annual mean temperatures (about 4 °C for the 3 sites).

4.5 Parameter Sensitivity Analysis

4.5.1 Influence of the thermal susceptibility of the fatigue parameter ε_6 and of the modulus

Calculations of equivalent temperature have been carried out, for the reference case, with the 5 experimental laws of variation of ε_6 with temperature, presented on figure 1. The results, presented in table 2, show that the value of θ_{eq} depends largely on the thermal susceptibility of the fatigue parameter ε_6, with differences of up to 7°C, depending on the chosen law.

Table 2 : Influence of thermal susceptibility of ε_6 on θ_{eq}

Law of variation of ε_6	2002-Charente	2005-Vosges	2008-Loire-Atlantique
$\varepsilon_6(\theta)\cdot(E(\theta))^{0,5} = constant$	19.7 °C	17.7 °C	19.9 °C
Law 1 (Domec, 2005)	18.3 °C	20.1 °C	18.7 °C
Law 2 (De la Roche, 1997)	26.1 °C	21.4 °C	24.2 °C
Law 3 (Moutier, 1991) 20/30 pen	18.4 °C	18.6 °C	19.3 °C
Law 4 (Moutier, 1991) 60/70 pen	19.3 °C	17.8 °C	19.5 °C
Law 5 (Moutier,1991) 80/100 pen	19.7 °C	17.4 °C	19.8 °C

Similar calculations have been performed, for the reference case, with 4 different laws of variation of the modulus of bituminous mixes with temperature *E(θ)* (see figure 7): two mean laws available in the ALIZE database, for a base course asphalt material (Grave Bitume) and for a dense asphalt concrete (BBSG) and two experimental laws, coming from complex modulus tests.

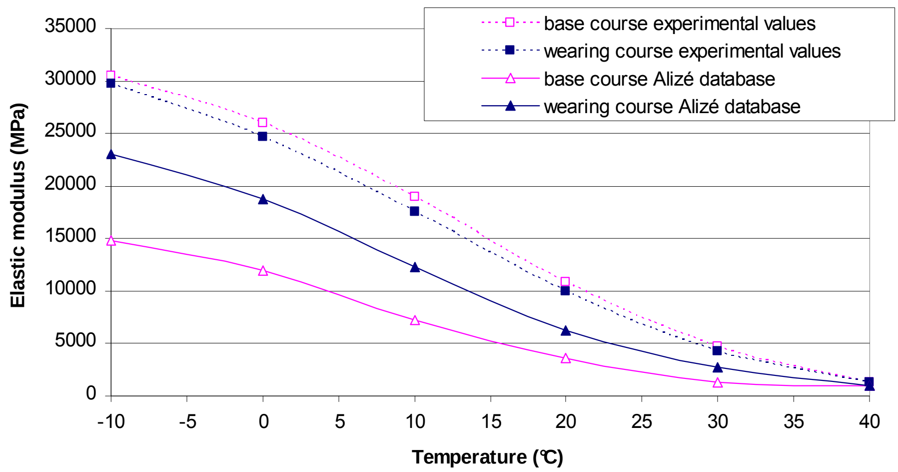

Figure 7: curves of variation of modulus at 10 Hz with temperature considered in the simulations

Table 3 shows the influence of the chosen law of variation of modulus on θ_{eq}. Depending on the chosen law, differences of up to 4°C are obtained. This shows that the variations of modulus with temperature have an important influence on the equivalent temperature (as for the fatigue parameters), and that using experimental values of $\varepsilon_6(\theta)$ and $E(\theta)$ is very important to estimate accurately the damage, and consequently the equivalent temperature.

Table 3 : Influence of thermal susceptibility of the modulus on θ_{eq}

θ_{eq}	2002-Charente	2005-Vosges	2008-Loire-Atlantique
modulus susceptibility: ALIZE data	20.5 °C	17.7 °C	21.1 °C
modulus susceptibility : experimental	23.3 °C	20.5 °C	25.2 °C

4.5.2 Influence of the hourly traffic distribution and pavement structure

To evaluate the influence of the traffic distribution on the equivalent temperature, calculations of $\square_{eq}$ have been made for the reference case, using the mean distribution of traffic defined in 4.1, and a uniform distribution, with the same traffic each hour. The results, presented in table 4, confirm that the hourly distribution of the traffic (in relative percentage) has only a low influence on the calculation of $\square_{eq}$. This confirms that to estimate $\square_{eq}$, the exact hourly distribution of traffic is of secondary importance (compared with the climatic data, or material parameters). A typical mean traffic distribution (as calculated here) is sufficient, except, of course, in case of very specific traffics, concentrated during certain hours, or periods of the year. Finally, the effect of changing the pavement structure has been tested, by comparing the results obtained for the reference structure, and for a second thicker structure, 8cm AC/ 13cm RBA/ 13 cm RBA, with the temperature data from the 3 experimental sites. The results, presented in table 4, indicate that θ_{eq} is not very sensitive to the thickness of the structure.

Table 4 : Influence of the hourly traffic distribution and pavement structure on θ_{eq}.

Pavement structure	Traffic	2002-Charente	2005-Vosges	2008-Loire-Atl.
8 AC / 8 RBA / 8 RBA	Mean measured traffic	20.5 °C	17.7 °C	21.1 °C
8 AC / 8 RBA / 8 RBA	Uniform distribution	20.0 °C	17.0 °C	20.4 °C
8 AC / 13 RBA / 13 RBA	Mean measured traffic	21.7 °C	17.9 °C	21.0 °C

5 INFLUENCE OF EQUIVALENT TEMPERATURE VARIATIONS ON PAVEMENT DESIGN

To conclude this analysis, table 5 presents results of calculations showing the influence of variations of the equivalent temperature (between 15 and 24 °C) on pavement design life. The calculations have been made for the reference pavement considered in 4.4 (8cm AC / 8cm RBA / 8cm RBA), taken from the French pavement design catalogue (SETRA-LCPC, 1998). This structure is designed for 20 years, for a total cumulated traffic of 2.25 million ESALs.
The first part of table 5 gives, for the reference pavement, values of the tensile strain ε_t at the bottom of the bituminous layers, and values of the fatigue parameter ε_6, considering 3 different laws of evolution of ε_6 with temperature. Then, the second part of the table gives the corresponding design lives (in years), calculated using the French pavement design method, and assuming that the average daily traffic is the same. It can be concluded that:

- With the law of variation of ε_6 used routinely in the pavement design method, the design life decreases slightly when the temperature increases, from 20 years for θ_{eq} = 15°C (standard hypothesis of the design method) to 9 years for θ_{eq} = 24°C.
- With the second, experimental, law of evolution of ε_6 (de le Roche, 1997), the values of ε_6 are much smaller, and increase much less with temperature, and this has a very strong

influence on the design life which is equal to 11.9 years for 15 °C and decreases to only 1.5 years for 24 °C; the third law of ε_6 gives intermediate results.

Table 5: Influence of the equivalent temperature on the design life of a reference pavement, considering different laws of variation of ε_6 with temperature.

	Equivalent temperature	15°C	18°C	21°C	24°C
	Calculated ε_t (µstrain)	85	100	119	138
Fatigue parameter ε_6 (µstrain)	$\varepsilon_6(\theta).(E(\theta))^{0,5}$= *constant*	104.4	115.8	129.7	146.4
	Law 2 (De la Roche, 1997)	93.1	95.1	97.2	99.4
	Law 3 (Moutier, 1991) 20/30 pen	100.5	108.2	116.7	125.8
Design life (years)	$\varepsilon_6(\theta).(E(\theta))^{0,5}$= *constant*	20,2	15,3	11,5	9,0
	Law 2 (De la Roche, 1997)	11,9	5,.9	2,7	1,5
	Law 3 (Moutier, 1991) 20/30 pen	17,4	11,2	6,8	4,7

The results of table 5 clearly show that:

- Design of bituminous pavements is very sensitive to climatic conditions, and a change of several degrees of the equivalent temperature can modify largely the design life of the pavement, because of the thermal susceptibility of bituminous materials.
- To take into account correctly the temperature variations, it is necessary to use real experimental values of modulus and also fatigue resistance at different temperatures: in table 5, depending on the law of variation of ε_6, the design life can vary by a factor of 5.

The predictions made here, on the basis of laboratory fatigue tests, indicate a significant decrease of pavement life, when the temperature increases (in the tested temperature range, 15-24 °C). These results need to be confirmed by observations on real pavements.

6 CONCLUSION

The objective of this paper was to discuss the effect of temperature variations on design of bituminous pavements, with the approach of the French pavement design method. The analysis has been performed using the notion of "equivalent temperature" θ_{eq}, which is defined as the constant temperature leading, for a given pavement, to the same fatigue damage as the real variations of temperature in the pavement.

Calculations of equivalent temperature θ_{eq} have been performed for a reference bituminous pavement, using temperature data from 3 sites, corresponding to different French climatic conditions. The results show that taking into account real temperature data leads to significant differences of θ_{eq} for the 3 sites, and thus significantly different pavement lives.

A sensitivity analysis has also indicated that using real experimental values of modulus and fatigue parameters, obtained at different temperatures, is of key importance to determine correctly θ_{eq}. For instance, an example has shown that using real experimental values of ε_6 at different temperatures, instead of the empirical relationship $\varepsilon_6(\theta)\cdot(E(\theta))^{0,5} = cons\tan t$, can modify the design life by a factor of 5. The thickness of the pavement structure, the shape of the temperature profile with depth, and the hourly distribution of the traffic seem to have a lower influence.

The calculations of θ_{eq} presented in this paper are only examples, obtained for a limited number of cases, but they show that using a single, constant temperature for pavement design, as done in many design methods, is a very simplifying assumption. It is planned to continue this work by using other experimental pavement temperature data, and also to try to compare the design predictions obtained at different temperatures with real pavement behaviour. The final objective is to propose an improved approach to take into account temperature variations in the French pavement design method, in particular to adapt this method to other climates.

REFERENCES

ALIZE-LCPC, 2005. pavement design software: http://www.lcpc.fr/fr/produits/alize/doc/alize.pdf

De la Roche C., Rivière N. 1997. *Fatigue behaviour of asphalt mixes: Influence of laboratory test procedures on fatigue performance,* 8th Int. Conference on Asphalt Pavements, Seattle, USA, August 1997, pp 899-917.

Domec V., Breysse D., de la Roche C., Yotte S. 2005. *Caractérisation de la durée de vie en fatigue des enrobés bitumineux en conditions de trafic simulé et de température*, Revue Européenne de Génie Civil, 9/2005, pp 385-400.

Lundström R., Di Benedetto H., Isaacsson U. 2004. *Influence of asphalt mixture stiffness on fatigue failure*, Journal of Materials in Civil Engineering ASCE, vol16 n°6, December 2004, pp 516-525.

LCPC – SETRA, 1994. *Conception et dimensionnement des structures de chaussées*. Guide technique, Décembre 1994.

Mauduit C., Duval R. 2008. *Prise en compte des températures équivalentes dans le dimensionnement des chaussées*, rapport N°2, LR Nancy, opération 11P063 : Outils avancés de calcul et de dimensionnement des structures de chaussées. Dossier 200864007.

Moutier F. 1991. *Etude statistique de l'effet de la composition des enrobes bitumineux sur leur comportement en fatigue et leur module complexe*, Bulletin de Liaison des Laboratoires des Ponts et Chaussées, n°172, pp71-79.

SETRA – LCPC, 1998. *Catalogue des structures types de chaussées neuves*, edition 1998.