Estimation of the Equivalent Design Temperature of a Pavement in Burkina Faso

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Abstract: The bituminous pavements of the city of Ouagadougou (Burkina Faso) are made using old design methods which take into account the climate from the notion of equivalent temperature. Thus an equivalent temperature of 30 °C is often used for the design of bituminous pavements. The observation that has been made is that this temperature does not currently make it possible to reduce the problems of early degradation of the pavements linked to meteorological fluctuations. The objective of this article is to propose a numerical approach for determining the equivalent temperature from temperature measurements taken at the surface of the pavement. This approach consists in jointly using the Alizé-Lcpc sizing software and the Comsol Multiphysics software using the finite element method. For a four-layer bituminous pavement, located at 12.38° North and 1.48° West, in Ouagadougou, consisting of a surface course of bituminous concrete of 8 cm and a base course of gravel bitumen of 16 cm, an equivalent temperature of 35 °C was obtained.

Key words: Asphalt mixes, pavement design, equivalent temperature.

Abbreviations

- AC: wearing course
- BC: base course
- LITHO or Lithostab: foundation course
- LCG: lateritic clay gravel
- LCPC: Central Road and Bridge Laboratory
- NR4: National Road 4
- AASHTO: American Association of State Highway and Transportation Officials
- $E_{\text{asphalt}}$: modulus of rigidity of the asphalt MPa
- $E$: Young material modulus MPa
- $\nu$: Poisson ratio
- $D$: thermal diffusivity of the material $\text{m}^2\text{s}^{-1}$
- $C_p$: mass heat capacity of the material $\text{Jkg}^{-1}\text{°C}^{-1}$
- $\rho$: density of the material $\text{kgm}^{-3}$
- $\alpha_{th}$: coefficient of thermal expansion $\text{mm}^2\text{m}^{-2}\text{°C}^{-1}$
- $\theta_t$: temperature in the pavement body °C
- $\theta_{eq}$: equivalent temperature °C
- $\epsilon(\theta_t)$: tensile deformation at the base of the asphalt gravel

1. Introduction

A bituminous pavement must be designed to withstand the stresses resulting from traffic and weather conditions. It must facilitate the diffusion of tangential and longitudinal forces related to traffic in its foundation layer. The application of a rolling load on the pavement produces a bending of the layers which causes traction and compression at the base of the surface layers. The sizing therefore consists of determining the materials and choosing the thicknesses of the pavement layers to support a given traffic [1]. Depending on the pavement structure, two
types of approaches are used for pavement design: the empirical approach with the AASHTO (American Association of State Highway and Transportation Officials) [2] method and the analytical-empirical approach with the French LCPC-SETRA method [3].

The AASHTO method is based on the results of tests carried out on more than 500 roads sections from 1950 to 1993 by AASHTO Road in the United States of America. The thicknesses of the different pavement layers are then determined by the AASTHO abacus of structural numbers [4, 5].

The French pavement design method is based on both theoretical calculations and experiments (LCPC-SETRA, 1994). It combines the theoretical analysis of pavement mechanics, the results of laboratory tests on the fatigue behavior of pavement materials and the data obtained by observing the operation of pavements, which will be implemented in the Alizé-lcpc software [3]; the linear elastic model of BURMISTER [6] is used.

The essential parameters for the theoretical calculations of the French pavement design method are the traffic, the desired service life of the pavement, the descriptive parameters of the supporting soil and the bedding materials, the latter making it possible to calculate the admissible stresses.

For thirty years, the sizing of bituminous pavements in Burkina Faso has been carried out from the practical guide to pavement sizing [1] for relatively low traffic compared to the current mechanical efforts encountered on the bituminous pavements of the city from Ouagadougou.

Indeed, the French sizing method [3] used in Ouagadougou takes into account the traffic and the climate from the equivalent temperature. This temperature to respond to current traffic and weather conditions should be estimated again in order to perform a better sizing of the pavements in order to improve their lifespans.

We propose in this article to estimate the equivalent temperature of the city of Ouagadougou. This estimate is based on experimental and numerical work to determine the temperatures at the surface and in the base layer as well as the mechanical characteristics of the pavement, in particular the complex modulus of the asphalt layers and the damage associated with the traffic/temperature couple.

2. Materials and Methods

2.1 Structure of the Bituminous Pavement

The carriageway of NR4 (National Road 4), located east of the city of Ouagadougou was selected as the study carriageway. It is a semi-rigid, draining pavement, made up of 4 layers: a wearing course of bituminous concrete (AC), a base course of gravel bitumen (BC), a foundation layer of Lithostab (LITHO) and a LCG (lateritic clay gravel) subgrade as shown in Fig. 1.

2.1.1 Bituminous Coated Layers

Bituminous mixes (AC and BC) are heat-sensitive materials composed of a mixture of crushed granites from the Yimdi industrial quarry located southwest of the city of Ouagadougou and pure 35/50 bitumen. The granular classes having been used for the formulation of the AC are 6/10, 4/6, 0/4 and those having been used for the formulation of the BC are 0/4, 4/6, 6/10, 10/14.

2.1.2 Foundation and Subgrade Courses

Foundation course (LITHO) comes from a mixture of LCG from the locality of Banogo located 10 km east of the city of Ouagadougou, with 30% crushed granites, according to the requirements of the lithostabilization process [7].

The LCG is a residual soil of tropical weathering, consisting of a mixture of particles with dimensions generally between 2 and 20 mm (pisolites, concretions or more or less hard nodules and/or quartz nodules) and lateritic coloured clay most often reddish or other (sometimes grey, further north in Burkina Faso).

As part of this work, we will focus on bituminous coated layers (AC, BC).

The thermal and geotechnical properties of the two asphalt layers are shown in Table 1.
**Table 1** Thermal and geotechnical properties of bituminous asphalt layers.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Layer thickness (cm)</th>
<th>Young modulus $E$ (MPa) at $10^\circ C$</th>
<th>Poisson ratio $\nu$</th>
<th>Coefficient of expansion $\alpha_{th}$ $(1/K)$</th>
<th>Thermal conductivity $k$ ($\frac{W m}{K}$)</th>
<th>Density $\rho$ ($\frac{kg}{m^3}$)</th>
<th>Heat capacity $C_p$ $(\frac{J kg}{K})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wearing course</td>
<td>8</td>
<td>1,300</td>
<td>0.35</td>
<td>$1.1 \times 10^{-5}$</td>
<td>2</td>
<td>2,350</td>
<td>870</td>
</tr>
<tr>
<td>Base course</td>
<td>16</td>
<td>2,700</td>
<td>0.35</td>
<td>$1.1 \times 10^{-5}$</td>
<td>1.9</td>
<td>2,350</td>
<td>900</td>
</tr>
</tbody>
</table>

2.2 Numerical Approach

2.2.1 Numerical Modelling with Finite Element Software

The numerical resolution with the commercial tool ComsolMultiphysics 5.2 [8] consists in solving the heat transfer problem described by the partial differential equations of the temperature together with the boundary conditions using the finite element method [9, 10]. It goes through the stages of defining the geometry of the pavement, the mesh of the pavement, the definition of the physical properties of the materials and the boundary conditions, the numerical resolution and the analysis of the results (post-processing). This makes it possible to obtain several pieces of information on the structure, including the temperature profile at any position in the pavement.

2.2.2 Sizing with Alizé-lcpc

The Alizé-lcpc software is a numerical tool based on the rational pavement design method [3].

Its use revolves around three main phases which are: the choice of the type of structure and the materials, the determination of the admissible stresses in the different materials, and the determination of the thicknesses of the different layers of materials.

The calculation model allowing the determination of the mechanical parameters illustrated is based on the Burmister’s model [6] which is based on the mechanical modeling of the pavement structure by a semi-infinite solid mass, consisting of a superposition of layers of material of constant thickness with linear isotropic elastic behavior with the descriptive parameter of each material, the elastic modulus $E$ and the Poisson’s ratio $\nu$.

2.3 Method of Calculating the Equivalent Temperature

2.3.1 Definition of Equivalent Temperature

The equivalent temperature is the temperature for which the corresponding rate of degradation is equal to the average rate of degradation during a year. The equivalent temperature is determined by applying the Miner rule [11]. It is given by the following formula:

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

(1)

By introducing into Eq. (1), the expression of the law of fatigue one obtain:

$$
\frac{1}{N(\theta_{eq})} = \left[ \sum_i n_i(\theta_i) \left( \frac{\varepsilon_{th}(\theta_i)}{\varepsilon(\theta_i)} \right)^{\frac{1}{\beta}} \right] \times 10^{-6}
$$

(2)

Thus having the elementary damage ($d_{eq}$), $\frac{1}{N(\theta_{eq})}$, $\theta_{eq}$ is obtained from the curve giving the variation of the damage with temperature.

The constant temperature called equivalent temperature $\theta_{eq}$ represents the temperature at which the sum of the damages undergone by the pavement during one year, for a given temperature distribution is equal to the damage that the pavement would undergo subject to the same traffic at the constant temperature $\theta_{eq}$.

2.3.2 Equivalent Temperature Calculation Procedure

The SETRA-LCPC guide assumes that the temperature distribution in the thickness of the bituminous layers is uniform and that the traffic is assumed to be uniform throughout the year.

Thus, the calculation of the equivalent temperature
The estimation of the equivalent design temperature of a pavement in Burkina Faso is carried out by proceeding as follows:

The temperatures $\theta_l$ are recorded in the pavement over a certain depth of the bituminous layers (generally on the BC) of the pavement over the course of a year. The reading of the temperature over a year corresponding to 365 days, has the purpose of assigning a percentage to the distribution of the different temperature values. This calculation is essential because it is assumed that the traffic is uniformly distributed over the year and that the values of $\frac{n_l(\theta)}{\sum n_l(\theta)}$, a linear function, correspond to the annual distribution percentages temperatures.

We determine the tensile deformation $\varepsilon(\theta_l)$ at the base of the base in gravel bitumen.

The knowledge of $\varepsilon_0(\theta_l)$ which corresponds to the amplitude of request which is necessary to apply to obtain a lifespan of $10^6$ cycles, makes it possible to deduce the elementary damage.

The elementary damage according to each temperature recorded is then determined in the bituminous layers of the pavement over the course of a year. Thus the damage corresponding to a temperature $\theta_l$ is given by the following relation:

$$d(\theta_l) = \left( \frac{\varepsilon_0(\theta_l)}{\varepsilon(\theta_l)} \right)^2 \times 10^{-6} \quad (3)$$

The sum of the product of the elementary damage by the duration (%) during the year with the traffic distribution allows through Eq. (4) to calculate $\frac{1}{N(\theta_{eq})}$:

$$\frac{1}{N(\theta_{eq})} = \sum_l \left[ \frac{n_l(\theta_l)}{\sum_l n_l(\theta_l)} \times d(\theta_l) \right] \quad (4)$$

$\theta_{eq}$ is finally deduced from the damage curve.

According to the previously detailed procedure, the calculation of the equivalent temperature goes through a determination of the temperature distribution in the body of the pavement, of the admissible deformation $\varepsilon_0(\theta_l)$ and the tensile deformation $\varepsilon(\theta_l)$ at the base of the gravel bitumen layer for each temperature $\theta_l$ recorded in the body of the pavement and the elementary damage to the pavement associated with these temperatures.

2.4 Determination of the Temperature Distribution in the Body of the Pavement

The distribution of the temperature in the body of the pavement necessary for the needs of the calculation of the equivalent temperature is that at 15 cm depth of the pavement at 11 cm in the Grave Bitumen. The determination of this temperature distribution was obtained by first taking temperature measurements on the surface of the roadway between 6:00 a.m. and 6:00 p.m. GMT over the period from February 6 to April 15, 2018 using an infrared thermometer, the 830-T2 model from the Testo brand (Fig. 1). The simulated temperatures for a time interval of one hour (3600 s) in the gravel bitumen are obtained after solving the heat transfer equation (Eq. (5)) using Comsol Multiphysics 5.2 software, with boundary conditions: at the surface of the pavement, the temperature measured at the surface of the pavement; the support layer of the thermally insulated pavement; thermal continuity at the interface between the different temperature layers.

The bituminous layers of the pavement are considered a linear and isotropic elastic bilayer system. The contact is assumed to be perfect between the AC layer and the BC layer. The heat transfer in these...
different layers is governed by the conduction equation given by the following relation:
\[ \Delta T = \frac{1}{D} \frac{\partial T}{\partial t} \]  
(5)

where \( T \) the temperature of the layer; \( D = \frac{k}{\rho c_p} \) and \( k \) the diffusivity and thermal conductivity of the layer, \( \rho \) the density of the layer and \( C_p \) heat capacity

The temperature of the initial condition chosen for bituminous layers is 35 °C. The variation of the surface temperature as a function of the simulated temperature at a depth of 15 cm of the pavement structure (Fig. 2), tells us that for simulated temperatures in the BC below 35 °C, the temperature at the surface of the pavement is lower than that in the BC, this is explained by the fact of the initial temperature condition of 35 °C. This would mean that the temperature in the body of the pavement is higher than that of the surface. Beyond 36 °C the surface would warm the body because of the large temperature difference that can be observed.

The temperatures measured at the surface of the pavement for the simulated temperature of 36 °C in the body of the pavement are above 45 °C (maximum design temperature with the Alizé-lcpc software).

In addition, the work of Koudougou et al. [12], tells us that in scorching conditions of the city of Ouagadougou, the temperatures observed on the surface of the road are well above 45 °C. It could therefore be said a fortiori that Alizé-lcpc software would underestimate in its test of sizing the surface layer, the scorching weather conditions of the city of Ouagadougou.

On the other hand, the body of the pavement (15 cm in the BC), the temperatures are always below 45 °C, in terms of rigidity, the software would make it possible to estimate satisfactorily the behavior of the BC in the Burkinabe climate context.

From the point of view of the percentage distribution of the temperature in the body of the pavement (Table 2), it can be seen that it is higher for the temperature of 35 °C.

Fig. 2  The evolution of the elongational strain at the base of the BC as a function of temperature.
3. Results and Discussions

The determination of the equivalent temperature passes from the preliminary steps of estimating the parameters of permissible deformation, elongation deformation and damage.

3.1 Determination of Permissible Deformation $\varepsilon_6(\theta)$

According to Setra-LCPC (1984), the permissible deformation $\varepsilon_6(\theta)$ for a temperature any $\theta$ in temperate climatic conditions with positive temperatures can be connected to the module complex $E(\theta)$ at the same temperature of the bituminous asphalt layer through the relationship:

$$\varepsilon_6(\theta) \cdot E(\theta)^{0.5} = \text{constant}$$  (7)

From the experimental results obtained from the fatigue curve of the BC, the permissible deformation (Fig. 3) is determined from Eq. (7) corresponding to each temperature simulated with Comsol Multiphysics 5.2 in the BC after an estimate with Alizé-lcpc of the complex modules (Fig. 4) corresponding to these temperatures when they are less than or equal to 45 °C (temperature limit of the Alizé-lcpc software). The comparison of complex modulus and permissible strain graphs tells us that the permissible strain is inversely proportional to the complex modulus. This is explained by the fact that under the assumption of linear elasticity, a higher modulus material will have better resistance to deformations. This would result in a lower permissible deformation.

3.2 Determination of Elongational Strain $\varepsilon(\theta)$

The elongational strain in the bitumen bass for simulated temperatures using Comsol Multiphysics5.2 software was determined over a temperature range from 0 to 45 °C with the Alizée-lcpc software. The resulting deformation profile shows us an increase as a function of temperature (Fig. 5). Indeed, many studies have shown a loss in rigidity of bituminous asphalt with temperature [12]. This is characterized by a decrease in its Young’s modulus thus an increase in deformability. This phenomenon is therefore illustrated by the profile obtained from the elongation deformation.

![Fig. 3 Evolution of the permissible deformation as $\varepsilon_6$ a function of temperature according to SETRA-LCPC.](image-url)
3.3 Calculation of Elementary Damage and Determination of Equivalent Temperature

Elemental damage was deduced from the results of the determination of permissible and elongational strains at simulated temperatures in the BC using Eq. (4). The parabolic profile of the elementary damage is obtained and represented in Fig. 6 and reveals the existence of a maximum value of elementary damage close to 3 corresponding to the temperature of 35 °C. The temperature of 35 °C would seem to be a critical temperature, temperature at which, the damage is maximum.

By calculating the sum of the elementary damage corresponding to the temperature distribution in the body of the pavement a value of 2.936 is obtained.
This protected value on the damage evolution curve as a function of temperature, allows us to deduce an equivalent temperature equal to 35 °C.

4. Conclusion

The equivalent temperature generally used for pavement sizing in Burkina Faso is 30 °C. This research work made it possible to determine an equivalent sizing temperature of 35 °C using the Alizé-lepc software. At this equivalent temperature of 35 °C, according to the principle of sizing, they should increase the thicknesses of the layers of asphalt pavements to obtain an optimal sizing. However, this study allowed us to find that the Alizé-lepc software could underestimate the mechanical behavior of the bearing layer when the temperature is above 45 °C. Therefore, the question of the notion of the relevance of the choice of the equivalent temperature could be discussed in the Burkinabe climate context.

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References


