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Research Article

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Influence of the temperature under the pavement on deflection measurements with the Falling Weight Deflectometer

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Abstract The main focus of this paper is to study the mechanical behavior of the materials of a flexible and bituminous pavement structure. The measurement of the deflection will be the main indicator to estimate the condition of the pavement structure taking into account the influence of the temperature of the bituminous materials such as the bituminous concrete.

This research work was based on an advanced documentary research of the types of deteriorations and causes on the works conducted by the Senegalese Road Network Manager on the temperature survey works under pavement. Because of the strong dependence of the bituminous material on temperature and frequency, this study has allowed to simulate the integration of a temperature gradient in the pavement and its influence on the deflection measurement. Using a comprehensive thermal model, the temperature gradient in the pavement is reconstructed by measuring the ambient temperature, air velocity and sunshine.

Keywords deflection, temperature, deformation, gradient, mechanics

1. Introduction

In order to preserve the road heritage, the Government of Senegal has adopted an optimal management strategy for the development and maintenance of its classified road infrastructure, which is currently estimated at about 16,495 km, based on a three-year planning and programming of interventions [1].

The Road Data Bank (RDB) has opted, in accordance with the strategy of the Government of Senegal, for a long-term monitoring of the infrastructure. This monitoring is based on the regular updating of the data bank for a rational programming of maintenance works [1]. It is in this perspective that periodic campaigns of deflection measurements and counting of heavy vehicles are carried out in the national territory to measure the mechanical behavior of bituminous pavement materials to define the road maintenance technique to adopt following observed degradations [2].

Temperature gradients exist in the layers of bituminous materials, which can lead to a variation of modulus in these layers. With the improvement of models describing the behavior of pavement materials and thus the viscoelasticity of bituminous materials, temperature has become a significant parameter in behavior studies and diagnosis of structures under real conditions. Temperature in inverse pavement structure analysis programs have often been integrated as an empirical correlation formula [3].

This paper aims at improving the interpretation of deflection measurements with the falling weight deflectometer (FWD) on a flexible pavement structure. The operation of the devices (FWD, Deflectograph) has shown that their measurement assumptions lead to measurement bias [4]. Temperature and frequency have an important influence on the level of deflection, which, if not quantified, generate a strong variation in deflection. Hence the need to find a temperature correction factor to adjust the measured deflections [5].

2. Materials and Methods

Determination of the Characteristic Deflection

The falling weight deflectometer (FWD) test uses a weight that falls on a spring system mounted on a plate. Typically the applied stress can last for a period of 20 milliseconds. The principle of the FWD measurement is to reproduce the pavement loading caused by a passing heavy vehicle and measure the pavement response. The FWD simulates the passage of a heavy vehicle at a speed of about 70 km/h and records the induced deformation [6].

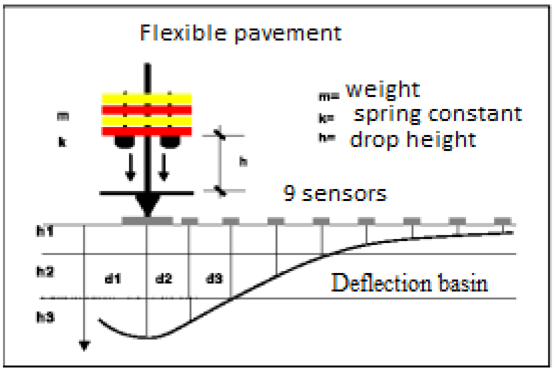

Figure 1: Deflection measurement with FWD

A deflection measurement campaign with the falling mass deflectometer (FWD) was conducted in 2020 on the Mbour-Joal departmental road (both directions) named D13100 on (384x2) points measured at the center of the FWD, at a distance of 0 meter from the eight other geophones. The structure pavement D13100 is flexible [7] :
Bituminous concrete wearing layer (AC): 5 cm,
Base layer in crude laterite: 23 cm
Foundation layer in crude laterite: 32.5 cm

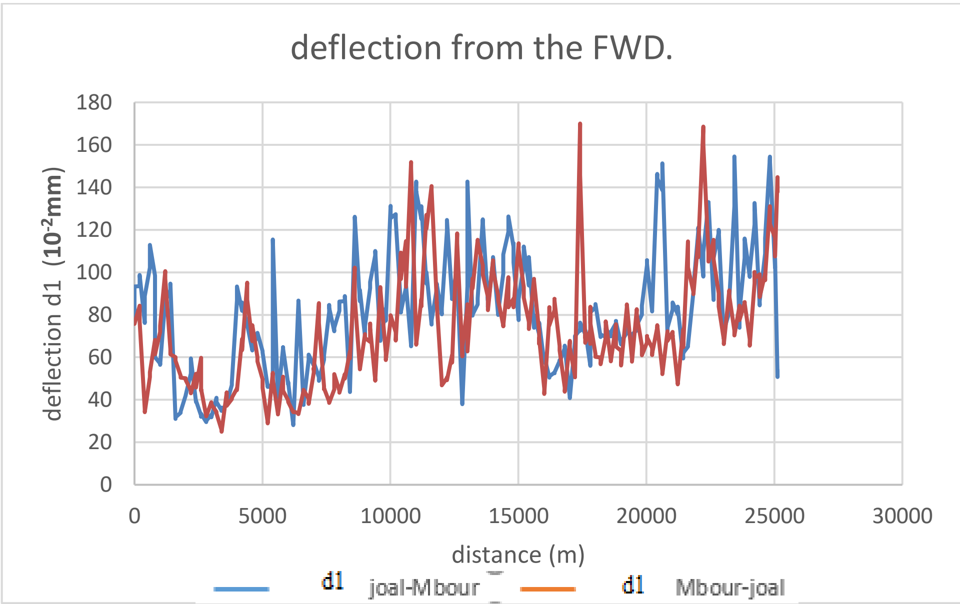

Figure 2: Deflection measurements on the FWD

The method of cumulative sums (Cusum) is used to identify the homogeneous zones. This technique of study of the evolution of the homogeneity of the results during a series of tests allows the division of the studied zone into homogeneous zones with regard to the studied parameter [8]. In our case this method is applied to determine the characteristic deflection (dc) in each homogeneous zone.
Using geophones, the FWD measures the maximum deflection at different impact points (usually every 50 m or 100 m) of a road (section) to be studied. Based on these maximum deflections (Figure 3), the road is subdivided

into homogeneous zones. These are road sections with very similar maximum deflection values and/or with a statistical behaviour monotone [9].

$$Cusum(P0) = 0$$

$Cusum(Pn) = Cusum(Pn - 1) + d(Pn) - dm$ with dm the average deflection.

We obtain for the maximum deflection d1 at 0 meter:

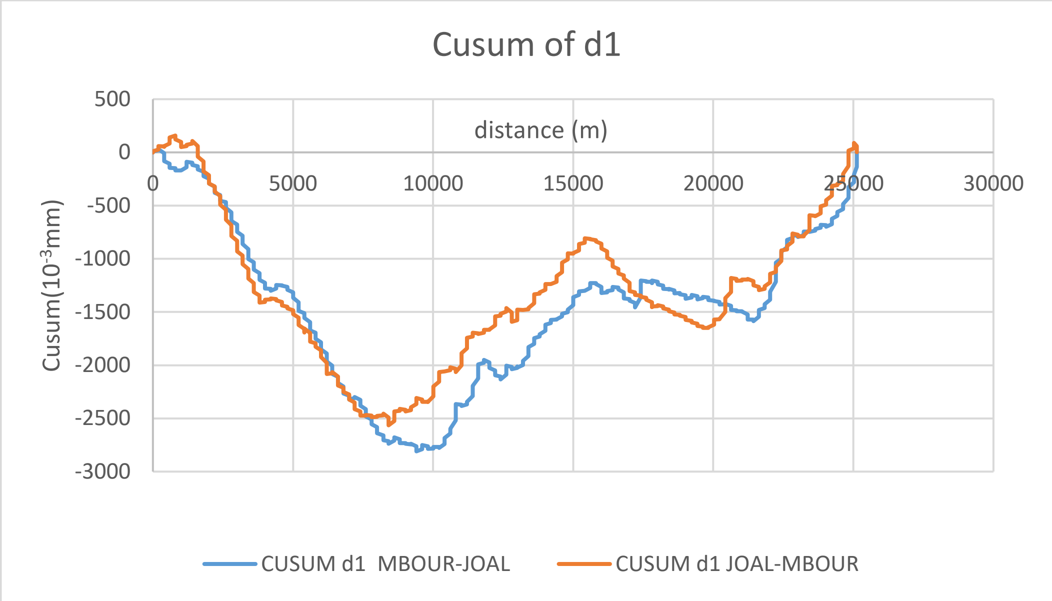

Figure 3: Cumulative sum curve Cusum

Thus (06) homogeneous zones are found on both directions of the D13100 section. The characteristic deflections are determined by the following expression on each homogeneous zone.

$$dc = dm + 1.3\sigma$$

Thermal Modelling

During the deflection measurement campaign on the D13100, the pavement surface temperatures are measured with the FWD machine.

The internal temperatures under pavements are not measured, temperatures values are calculated using the under-pavement heat equation and the under-pavement temperature measurements taken during the 2012-2013 survey.

The two sprues N°1 and N°2 are respectively 27 and 28 cm thick of bituminous materials (5 to 6 cm of AC and 23 to 22 cm of CB) at the Dakar site, Highway A1. The diagram below shows the position of the 8 sounders on the basis of depth [10] .

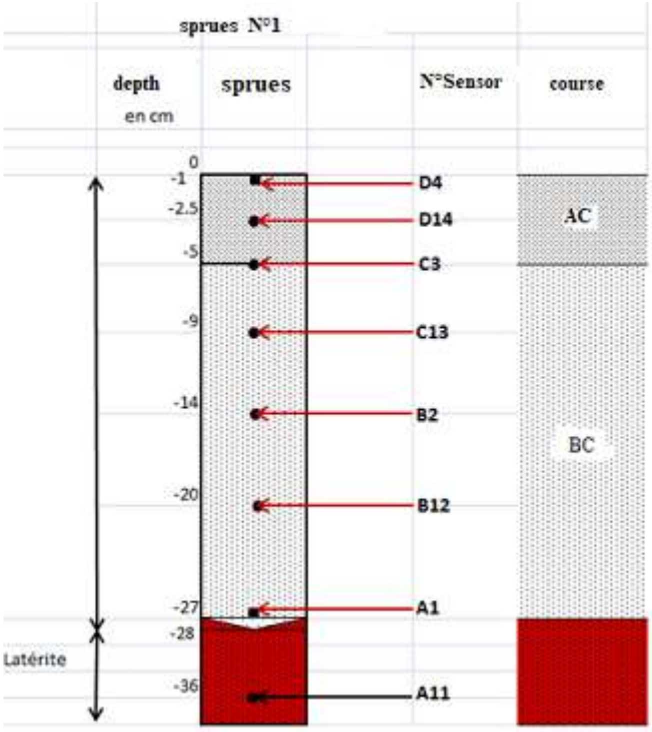

Figure 4: Sprues N°1

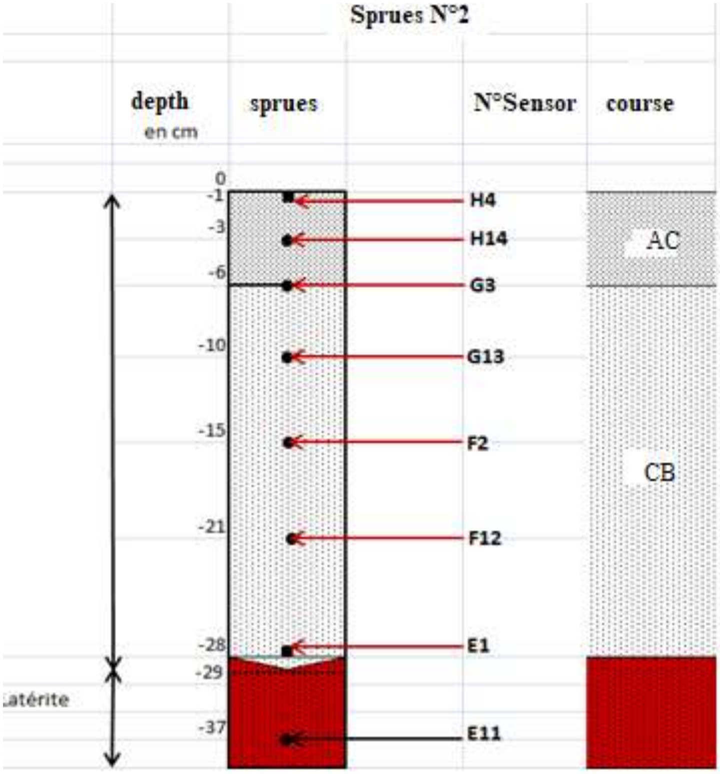

Figure 5: Sprues N°2

The black ball and the weather probe are respectively at 1.64 and 1.45 m above the ground as shown in the diagram below [10]:

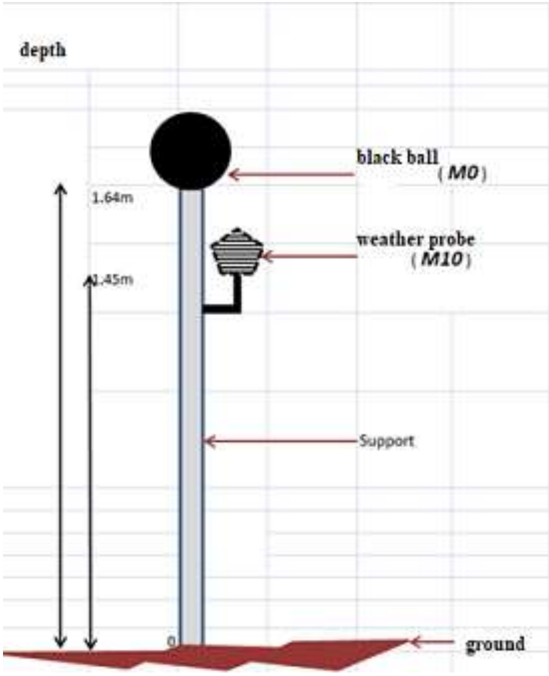

Figure 6: Air Temperature Measurement

The mechanical behavior of bituminous concrete is largely dependent on temperature, expanding with increasing temperature and contracting with decreasing temperature, the results being interpreted as thermal cracking. At high temperatures bituminous concrete is relatively soft and susceptible to rutting (permanent deformation), in accordance with repeated traffic loads. For these research purposes, measurements were made that predicted the surface layer temperature in situ and a model was adopted regarding the anticipation of the temperature variation of bituminous concrete over time [11].

A predictive model allowing to extrapolate the temperature under pavement is established. This model will be used to obtain temperatures at different depths (from 0 to 36 cm) on the D13100.

Expression of the temperature

The heat equation in ground is:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial z^2} + \Delta_r T\right) \qquad (2.1)$$

We suppose $\Delta_r = 0$

We assume that the pavement surface temperature is variable [12].

$$T = Ti + Tmoy.\cos[\mathrm{w}(\mathrm{t} - \mathrm{t0})] \qquad (2.2)$$

T : Initial temperature inside the pavement

Tmo : Average daytime temperature (degree).

w : Angular frequency $[w = 2\pi/24]$ (rad/hour)

$t0$: Time of maximum temperature during the day (solar midday). ($t0$ = 12.5 h).

With the change of variable we have

$$\theta = T - Ti = Tmoy.\cos[\mathrm{w}(\mathrm{t} - \mathrm{t0})] \qquad (2.3)$$

Equation number (2.1) gives:

$$\frac{\partial^2\theta}{\partial z2} = \frac{\rho i\ Ci}{\lambda i}\frac{\partial\theta}{\partial t} \qquad (2.4)$$

The boundary conditions are as follows:

- Z=0 $\theta = Tmoy.\cos[\mathrm{w}(\mathrm{t} - \mathrm{t0})]$
- Z= $\boldsymbol{\delta}\theta$ =0
- t= 0 θ =0

After solving equation number (2.4) by the method of separating of variables [13]:

$$\theta = Z(z).Y(t)$$

We obtain the following expression:

$$\theta(z,t) = \frac{Tmoy.cos[w(t-t0)]}{\cos(wt)}.e^{(-\sqrt{\frac{w}{2\alpha}}z)}.\left[\cos(wt).\cos(-\sqrt{\frac{w}{2\alpha}}z) - \sin(wt).\sin(-\sqrt{\frac{w}{2\alpha}}z) + i\left(\cos(wt).\sin(-\sqrt{\frac{w}{2\alpha}}z) + \sin(wt).\cos(-\sqrt{\frac{w}{2\alpha}}z)\right)\right] \quad (2.5)$$

α: The diffusivity of the material as [m^2 /s]

Here the temperature is more important on the real part of the complex solution

$$\theta(z,t) = \frac{Tmoy.cos[w(t-t0)]}{\cos(wt)}.e^{(-\sqrt{\frac{w}{2\alpha}}z)}.\left[\cos(wt).\cos(-\sqrt{\frac{w}{2\alpha}}z) + \sin(wt).\sin(-\sqrt{\frac{w}{2\alpha}}z)\right] \quad (2.6)$$

Hence the expression of the temperature T is given by :

$$T(z,t) = Ti + \frac{Tmoy.cos[w(t-t0)]}{\cos(wt)}.e^{(-\sqrt{\frac{w}{2\alpha}}z)}.\cos(wt - \sqrt{\frac{w}{2\alpha}}.z) \quad (2.7)$$

This model will be validated by the measurements of the temperature sounders realized during the campaign of the manager of the road network in 2012-2013 on the Kaolack road and the A1 Dakar-Diamniadio highway and to correct the measurements of deflections at the equivalent temperature of 34°C applied in the dimensioning of the pavements [14].

$d1(34) = Fc * d1(Tc)$ with Fc temperature correction factor and Tc temperature under pavement [5].

3. Results

Thermal model validation

The heat equation is verified at different times from 9:00 am to 4:00 pm with the maximum temperature measurements taken during the sounding campaign of temperature measurement of core well N°1 in well 1, see table 1.

Table 1: Maximum temperature measured over the period 10/07/2012-09/07/2013_Site Dakar Autoroute

Z_{sound} (m)	0	0.01	0.03	0.05	0.09	0.14	0.2	0.27	0.36
$T°_{max}$(C)	59	58.5	53.7	51.2	47.7	43.5	40.9	39.3	38.6

The expression of the temperature to be verified with the measurements of the table 1 [5].

$$T(z,t) = Ti + \frac{Tmoy.cos[w(t - t0)]}{\cos(wt)}.e^{(-\sqrt{\frac{w}{2\alpha}}z)}.\cos(wt - \sqrt{\frac{w}{2\alpha}}.z)$$

The temperature profile depending on the depth is given below at different times of the day.

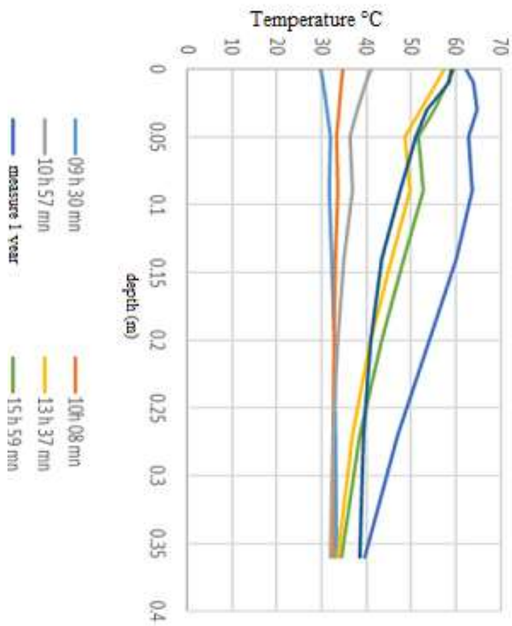

Figure 7: The temperature profile

Influence of the temperature in the deflection measurements at the center point of d1

Table 2: Characteristic deflection

Homogeneous zone	Temperature (z=0.03, t)	Characteristic deflection d1(10^{-2}mm)
1	31.2863633	84.24
2	33.9356427	68.99
3	37.9554004	109.31
4	52.2791583	122.77
5	64.6425261	126.89
6	55.2409469	133.08

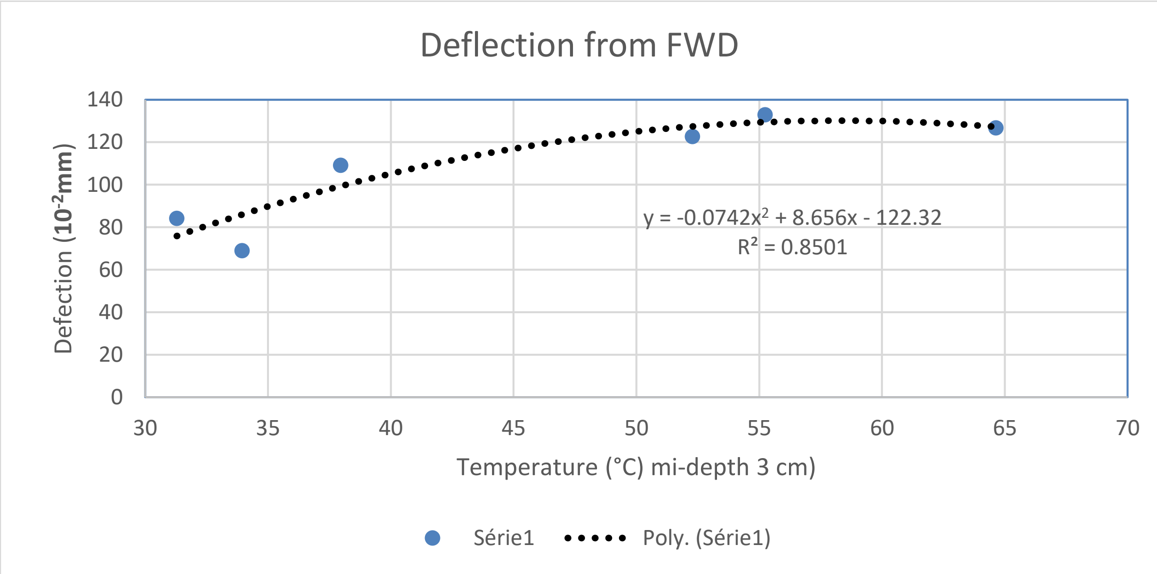

Figure 8: Temperature-deflection relationship

The design temperature of the pavement, called the equivalent temperature in Senegal, is 34 °C [14].

The deflections measured at different temperatures under the pavement will be adjusted to 34°C using a correction factor (Fc) obtained with the tendency on the D13100 axis of Mbour-Joal.

$$d1 = -0.0742Tc^2 + 8.656Tc - 122.32 \quad (3.1)$$

With Tc the temperature under the pavement at mid-depth of the bituminous concrete surface layer.

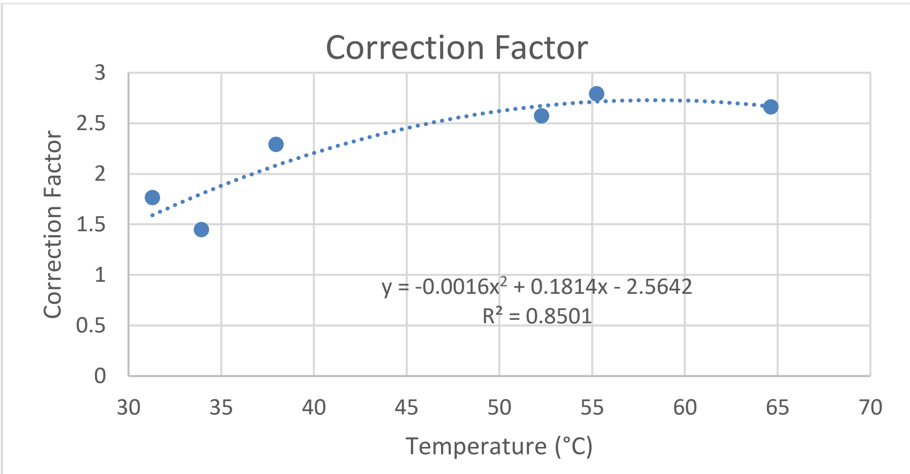

Figure 9: Correction factor

The deflection correction factor d1 found is given by the relation:

$$Fc = -0.0016Tc^2 + 0.1814Tc - 2.5642 \quad (3.2)$$

Thus the deflection adjusted to the equivalent temperature of 34°C obtained after measurement with the FWD is given by the following formula:

$$d1(34°) = d1(Tc)[-0.0016Tc^2 + 0.1814Tc - 2.5642] \quad (3.3)$$

Discussions

The temperature fluctuates with the deflection, hence the need to correct the deflection measurements obtained by considering the temperature of the bituminous concrete material in the case of the flexible structure. Thus, it is recommended not to make deflection measurements at temperatures higher than 34°C.

To compensate for these temperature effects, temperature correction regulations have been proposed in other countries as shown in the table below. They only allow to correct the maximum deflection. But these temperature corrections are only used on pavements with a bituminous structure.

Table 3: Deflection correction with other countries

French method	Spanish method	Belgium method
$d15 = \frac{dT}{1 + K * \frac{T-15}{15}}$	$d20 = \frac{200dT}{3T + 140}$	$d20 = k(T)dT$ $k(T) = 0.0003T^2 - 0.026T + 1.4$

dT: deflection at temperature T (surface or middle layer)

d15: deflecion at 15 °C

d20: deflexion at 20 °C

k: coefficient depending on the type of structure

A simultaneous campaign of temperature survey under pavement and deflection with the falling mass deflectometer on the national road system will allow the administrator of the road system to validate the tendency obtained on the Mbour-Joal departmental road.

Conclusion

The study of the characteristic deflection as a function of temperature under pavement with bitumen has been presented. The following evolution has been established:

$$d1 = -0.0742Tc^2 + 8.656Tc - 122.32$$

From the equivalent temperature under pavement of 34°C used in the design of pavements in Senegal, a temperature correction factor is used to correct the deflection measurements obtained with the FWD:

$$Fc = -0.0016Tc^2 + 0.1814Tc - 2.5642$$

to be extended to semi-rigid, thick bituminous and composite structures. The finalization of this work will contribute to the elaboration of the Senegalese pavement strengthening guide.

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