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Experimental Alternative to the Determination of the Thermal Dependence of the Complex Modulus of Asphalt Mixes in Dry Tropical Areas

Sidpouita Mathilde Koudougou[1,2*], Guy Christian Tubreoumya[2,3], David Yemboini Kader Toguyeni[1,2], Tégawendé Justin Zaida[1,2]

[1]Institut de Génie des Systèmes Industrielles de Textiles, Ecole Polytechnique de Ouagadougou, Ouagadougou, Burkina Faso
[2]Laboratoire de Physique et de Chimie de l'Environnement, Ouagadougou, Burkina Faso
[3]Université Joseph Ki-Zerbo, Ouagadougou, Burkina Faso
Email: *koudougoumathilde@yahoo.fr

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Abstract

Current pavement design methods do not allow for the reduction of early deformation of the surface layers of bituminous pavements in the city of Ouagadougou. Weather conditions combined with traffic, particularly during heat waves, are factors. The temperature at the surface of the bituminous pavement can reach 62˚C but the complex modulus associated with this temperature is not taken into account in the design, hence the interest in proposing laws of dependence of the complex moduli is taken into account in the maximum temperatures of the pavement surface. The objective of this paper is to propose an experimental method to determine the temperature dependence of the complex moduli of asphalt mixes for temperatures between 40˚C and 70˚C. This experimental method consists of performing axial compression tests on cylindrical asphalt specimens. It was applied to three different formulas of bituminous mixes, intended for the wearing course, obtained from mixes of crushed granites, granular classes 6/10, 4/6 and 0/4, pure bitumens of grade 50/70, 35/50 and modified bitumen of grade 10/65. The comparative study of the experimental results obtained with the results of a semi-empirical methodology revealed a root mean square deviation from the mean of between 6.58% and 14.8% of the norms of the complex moduli (modulus of rigidity) of the asphalt mixes for a fixed frequency of solicitations of 10 Hz. The consistency of these results with data from the literature led to the initial conclusion that asphalt mixes formulated with 35/50 and 10/65 bitumen would have better compressive strength than those formulated with 50/70 bitumen, for exposure temperatures between 40˚C and 70˚C. This experimental approach could be an alternative to the complex modulus test for determining the modulus of rigidity for design purposes under real pavement exposure conditions in the city of Ouagadougou during heat waves.

Keywords

Asphalt Mix, Complex Modulus, Axial Compression, Semi-Empirical Methodology

1. Introduction

Asphalt mixes are by definition viscoelastic and heat sensitive materials. The viscoelastic character is expressed through the complex modulus. The complex modulus of an asphalt mix expresses the stiffness of the mix under cyclic loading at small deformations ($<10^{-4}$; Airey *et al.* [1]), *i.e.* in the linear domain where the stiffness of the asphalt is independent of the state of stress or strain (Di Benedetto *et al.* [2]). The complex modulus E^* is a complex number given by the following relations:

$$E^* = E_1 + iE_2 = \left|E^*\right|\cos(\phi) + i\left|E^*\right|\sin(\phi) \tag{1}$$

$$\left|E^*\right| = \sqrt{E_1^2 + E_2^2} = \frac{\sigma}{\varepsilon} \tag{2}$$

$$\phi = \arctan\left(E_2/E_1\right) \tag{3}$$

E_1 is the real part of the complex modulus which characterises the elastic behaviour (stiffness) of the asphalt, E_2 is the imaginary part of the modulus which characterises the viscous behaviour (energy dissipated as heat), $\left|E^*\right|$ is the norm of the complex modulus (MPa), ϕ the phase shift between stress and strain represents the fraction of energy dissipated during the loading cycle, expressed in radians. The norm of the complex modulus $\left|E^*\right|$ is an approximation of the elastic modulus (YOUNG modulus) of an asphalt mix, which can be used for pavement design when the laws of elasticity are employed. Under these conditions, it is given by the ratio between the maximum stress and the maximum strain according to the following relationship:

$$\left|E^*\right| = \sigma/\varepsilon \tag{4}$$

σ is the maximum stress expressed in MPa and ε is the maximum strain expressed in m/m.

This modulus is called "dynamic modulus" in the Anglo-Saxon system (AASHTO TP 62-07, [3], ASTM D 3497-79, [4]) and "modulus of rigidity" in the European system (EN 12697-26, [5]).

In Burkina Faso, pavement design is based on the French rational method using the Alize-LCPC software (LCPC-SETRA, [6]). This software models the pavement according to Burmister's theory [7], as a multilayer, linear structure with perfect contacts. It is used to obtain mechanical responses of the pavement to traffic. For this purpose, it is necessary to integrate the value of the complex modulus of the asphalt layers. For design purposes, the complex modulus test is commonly carried out at 15˚C, 10 Hz, in European laboratories, by imposing sinusoidal loads on trapezoidal or cylindrical asphalt specimens. The Alizé software takes into account the thermo-sensitivity of asphalt mixes, based on an extrapolation of the experimental complex modulus value obtained at 15˚C, 10 Hz. The extrapolated complex modulus values cannot, however, exceed temperatures of 45˚C.

Some researchers have investigated the possibility of predicting the value of this modulus from the composition of the asphalt mix in order to obtain an order of magnitude that can be used in pavement design. The relationships found are derived from statistical studies based on the comparison of mechanical test results on several asphalt mixes with varying compositions. One can cite predictive formulas establishing relationships between the complex modulus of the binder and that of the asphalt mix by introducing the volume composition of the different constituents of the mix (mineral components, bitumen) as proposed by Ugé [8], Witczak *et al.* [9], Zeng *et al.* [10].

In view of the technical realities and in order to provide decision support for the construction of bituminous pavements, we propose a test to determine the complex modulus of bituminous mixes in temperature ranges between 40˚C and 70˚C. The temperature range chosen is justified by the fact that the work of Koudougou et Toguyeni [11] indicated that during a heat wave, temperatures at the surface of the pavement in the city of Ouagadougou could reach 62˚C.

2. Materials and Methods

2.1. Characterization of the Geotechnical Properties of Primary Materials

The primary materials, *i.e.* crushed granite aggregates and bituminous binders used for the formulation of asphalt mixes for the wearing courses of bituminous pavements in the city of Ouagadougou, were subjected to geotechnical characterisation tests.

2.1.1. Crushed Granite Aggregates

The crushed granite aggregates come from the Yimdi and Yagma quarries, whose geographical coordinates are respectively (N 12.30098˚, W 001.69862˚) and (N 12.38555˚, W 001.55814˚). The required granular classes were determined in terms of resistance to fragmentation (LA) and wear (MDV) in accordance with the requirements of standards NF P 18-573 [12] and NF EN 1097-1 [13].

2.1.2. Bitumens

The bitumens used for the asphalt mix design are of three different grades depending on the asphalt concrete (AC) formula. A 50/70 bitumen was used in asphalt concrete formula A, 35/50 bitumen for formula B and 10/65 modified bitumen for formula C. These different bitumens were identified by density measurements according to the requirements of standard AFNOR EN 12697-30 [14], penetrability index measurements according to the requirements of standard AFNOR XP T 66-064 [15], ring ball temperature (RBT) measurements according to the requirements of standard AFNOR NF EN 1427 [16].

2.2. Formulation of Asphalt Mixes

The bituminous mixes were formulated from the following granular classes of crushed granite 6/10, 4/6 and 0/4 and pure bitumen grades 50/70, 35/50 and modified bitumen 10/65.

The formulation of bituminous mixes is carried out in accordance with the requirements of standard NF P98-251-1 [17] and the table of dosages below (**Table 1**).

2.3. Production of Cylindrical Specimens

Cylindrical specimens were made to carry out axial compression tests to determine stiffness moduli. Three stages were necessary for their production: the preparation of the mixes, the production of the cylindrical specimens and their temperature setting. The preparation of the cylindrical specimens consists of a drying stage for the aggregates at 90˚C to 110˚C, followed by mixing of the dry aggregates at 150˚C to 160˚C ± 5˚C for 10 minutes. The temperatures of 150˚C and 160˚C correspond respectively to the temperatures at which the bitumen will be introduced into the mix.

The bitumen is heated to 100˚C for 10 minutes and then the aggregates + bitumen are mixed to form the mix at 150˚C and 160˚C for 5 minutes.

The cylindrical test specimens are made in accordance with the requirements of standard AFNOR NF 98-251-1 [17]. After preheating the moulds to 150˚C

Table 1. Dosage of asphalt mixes.

Asphalt Concrete formula	Components	Dosage (%)
Formula A	Crushed granite 6/10	30
	Crushed granite 4/6	25
	Crushed granite 0/4	45
	Pure bitumen grade 50/70	5.77
Formula C	Crushed granite 6/10	38.69
	Crushed granite 4/6	15.86
	Crushed granite 0/4	45.45
	Modified bitumen grade 10/65	5.4
Formula B	Crushed granite 6/10	43.3
	Crushed granite 4/6	16.5
	Crushed granite 0/4	34
	Pure bitumen grade 35/50	5.2

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and 160˚C ± 5˚C for 2 hours, the moulds are filled with mix at the same temperature by pouring in one kilogram. The moulds are then compacted at 60 kN for 6 minutes using a Controlab compression press.

Demoulding takes place 24 hours after compaction.

2.4. Determination of Stiffness Moduli of Asphalt Mixtures

As the thermal susceptibility of asphalt mixes is well known, the moduli of rigidity of asphalt mixes for temperatures of 40˚C, 50˚C, 60˚C, 70˚C were measured. These moduli were determined in two ways:

- By a non-conventional axial compression test following the Duriez test procedure.
- By using the empirical relation Heukelom and Klomp [18].

2.4.1. Axial Compression Tests

Axial compression tests on cylindrical specimens of asphalt mixes (height 10 cm × diameter 8 cm) were carried out in order to estimate the stiffness modulus of the mixes in an unconventional way.

The Duriez Laboratory Compression Press Controlab of the Building and Public Works Laboratory (**Figure 1**) was used to perform the experiments on the three types of asphalt mixes. Compression is achieved through the horizontal up and down movement of the lower press plate at a constant speed of 1 mm/s for 5 - 6 seconds; the upper plate fitted with a load cell is kept fixed and perfectly horizontal.

The press is connected to a digital platform allowing the acquisition of the force applied to the asphalt specimen for the associated movement of the plate.

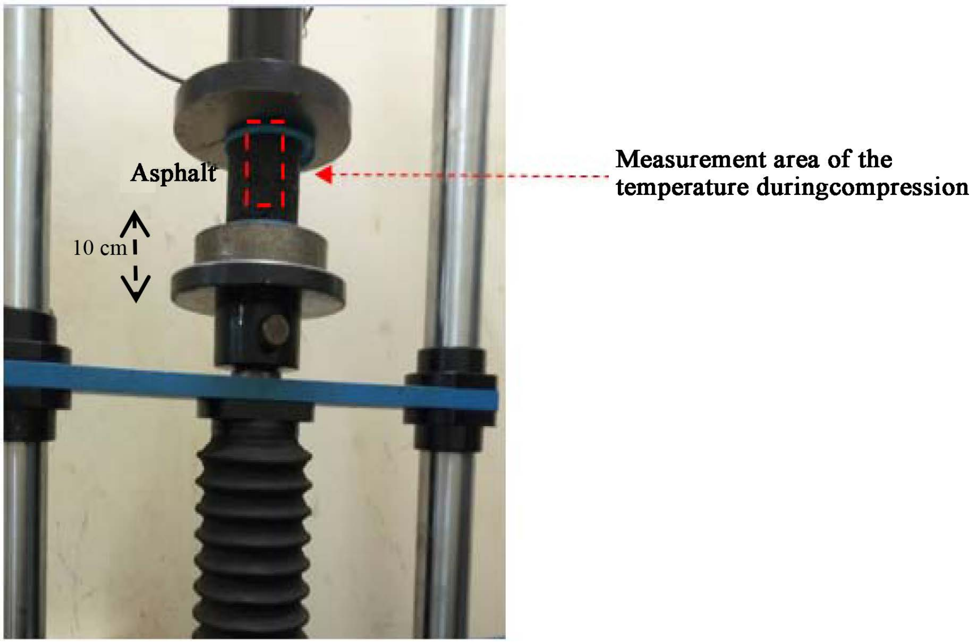

Figure 1. View of an asphalt sample placed on the Controlab compression press at the National Building and Public Works Laboratory.

2.4.2. Experimental Protocol

A test tube is placed in the oven, which has been heated to 100˚C, and brought to the desired temperature for a limited time (**Table 2**). Using a Testo infrared thermometer (830-T2), it is checked that the temperature is close to the desired temperature. This temperature of the test piece is always about 5˚C higher than the desired temperature, which allows the test piece to be placed on the plate of the Controlab compression press of the National Building and Public Works Laboratory. Once the specimen is placed on the press plate, the temperature at which the compression is to be carried out is measured using an infrared thermometer. The face temperature of the specimen is measured before and after the test as shown in **Figure 1**. If the measured temperature is equal to the desired temperature plus or minus 1˚C, compression is carried out. Each test was repeated on three samples of the same formula. For each test temperature, the software connected to the press records the instantaneous displacements of the plate associated with the compression force. From the geometry of the specimen, and the data obtained from the software, the stresses and strains of the specimen are determined from the following relationships:

$$\sigma = \frac{4P}{\pi d^2} \tag{5}$$

Avec σ the axial stress in (MPa); ε axial strain (m/m); P the axial axial load; Δh axial displacement (m), h height of the specimen for the measurement of Δh (m)

$$\varepsilon = \frac{\Delta h}{h} \tag{6}$$

2.4.3. Semi-Empirical Determination of the Modulus of Rigidity of Asphalt

The determination of the stiffness modulus of asphalt $\left|E^*\right|$ was also carried out through the empirical relation of Heukelom and Klomp [18] as it is adapted to asphalt mixes with a void ratio higher than 3%. This relationship relates the modulus of stiffness of bitumen S_b to the different volume fractions of bitumen and aggregates used in the mix design.

$$\left|E^*\right| = S_b\left[1+\frac{2.5}{n}\cdot\frac{C'_v}{1-C'_v}\right]^n \quad \text{Heukelom et Klomp [18]} \tag{7}$$

Table 2. Temperature setting of cylindrical specimens for axial compression.

Compression temperature of the specimen (˚C)	Duration of exposure in the study heated to 100˚C (minutes)
40	5
50	13
60	20
70	27

with $n = 0.83\log\frac{4\times 10^4}{S_b}$ and $C_c' = \frac{C_v}{0.97 + 0.01\left(100 - \left(g + b\right)\right)}$ (Van Draat *et al.* [19])

$$\text{with } C_v = \frac{g}{g+b} \tag{8}$$

S_b is the modulus of rigidity of bitumen taken from the Van der Poel [20] chart which gives the rigidity of bitumen as a function of frequency, temperature and the penetration index (PI) of bitumen, *g* and *b* are respectively the volume fraction of aggregates and that of bitumen.

The bitumen penetration index (PI), is calculated from the penetrability of the bitumen at 25˚C, P_{25}, and the TRB (softening point temperature) according to the relationship (Pfeiffer and Doormal, [21]):

$$\frac{20-\mathrm{PI}}{10+\mathrm{PI}} = \frac{\log \mathrm{P}_{25} - \log \mathrm{P}_{800}}{25-\mathrm{TRB}} \tag{9}$$

The TRB is considered to be the equiviscous temperature or temperature at which the penetrability P_{800} is 800 tenths of a mm.

The PI of bitumens always varies between −2 and +6. Thus, according to the classification of bitumens, bitumens with a PI lower than 0 are sol bitumens, those with a PI higher than 2 are gel bitumens and the other bitumens are sol-gel (Loeber *et al.* [22]).

It should be noted, however, that the relationship (7) remains rather limited because it does not take into account the size, shape and roughness of mineral materials defined solely by their volume. In particular, it neglects the internal friction of Such *et al.* [23].

The Van der Poel [20] chart gives the stiffness of bitumen as a function of frequency, temperature and the penetration index (PI) of the bitumen. From the PI and TRB obtained through the characterisation tests, the stiffness moduli of the bitumen's S_b for the frequency of 10 Hz were determined at temperatures of 20˚C, 30˚C,40˚C,50˚C and 60˚C.

Knowing the volume fractions of the aggregates and bitumen of the different formulas, the moduli of the complex moduli (stiffness moduli) were deduced from the relation (7).

3. Results and Discussions

The results of the Los Angeles and Micro-Deval tests according to the requirements are in accordance with the technical specifications (CCTP [24]). They are shown in **Table 3**.

The results obtained from the characterisation tests of the bitumens used for the formulation of the asphalt mixes are recorded in **Table 4**. These formulas have no limits of application. According to the bitumen classification model (Loeber *et al.*, [2]), the three bitumens used have PI lower than 0. They therefore belong to the soil bitumen class. Soil bitumens have an excellent resistance to fast loads but are more sensitive than gel bitumens (PI > 2) to slow loads and temperature variations.

The stiffness moduli obtained by the semi-empirical methodology combined with the Van Der Poel chart are given in Table 5.

Axial compression tests on cylindrical asphalt specimens at 40˚C, 50˚C, 60˚C and 70˚C were used to determine the secant moduli of stiffness associated with these temperatures.

The value of the secant modulus of stiffness is associated with each asphalt mix formula because it corresponds to the maximum stress applied to the mix; then a polynomial regression of the secant moduli as a function of temperature is carried out in order to obtain a law of evolution as a function of temperature. A similar polynomial regression process is carried out with the stiffness moduli derived from relationship 7, at the same temperatures and for a frequency of 10 Hz.

Table 3. Geotechnical properties of some granular classes of crushed granites.

Formula	Granular classes	LA (%)	MDV (%)
A	4/6.3	33.12	25
A	6.3/10	29.62	10
B & C	6.3/20	21.5	4.2
B & C	5/12.5	24.8	6.4

Table 4. Identification of bitumens.

Asphalt mix formula	Bitumen	Density	Penetrability	Temperature Ring Ball (˚C)	Penetration Index
Formule A	50/70	1.021	57.83	48	−1.38
Formule B	35/50	1.025	38.66	54.75	−0.658
Formule C	10/65	1.026	27.16	65.5	0.662

Table 5. Modulus of rigidity of bitumens obtained by semi-empirical methodology combined with the Van Der Poel [20] chart.

Temperature (˚C)	Grade of bitumen		
	50/70 Stiffness Modulus (Pa)	10/65 Stiffness Modulus (Pa)	35/50 Stiffness Modulus (Pa)
20	7.5×10^5	2×10^6	1.3×10^6
30	4.5×10^5	7×10^5	5×10^5
40	1.5×10^5	5×10^5	2.5×10^5
50	7.5×10^4	2×10^5	9.8×10^4
60	5×10^4	1×10^5	9.3×10^4
70	1.5×10^4	9×10^4	3.5×10^4

The moduli and squared errors obtained between the two modulus determination methods are reported in Table 6. Each modulus value is the arithmetic mean of the three specimens at the same temperature. The error between the two methods was obtained through the root mean square of the deviations from the mean:

$$\text{RMS} = \frac{\left|E^*_{\text{experimental}}\right| - \left|E^*_{\text{semi-empirical}}\right|}{2} \tag{10}$$

The representation of the moduli as a function of the test temperature indicates a drastic decrease of the moduli (Figure 2, Figure 3). These moduli are also found to be proportional to the bitumen grades. The moduli of mixes formulated

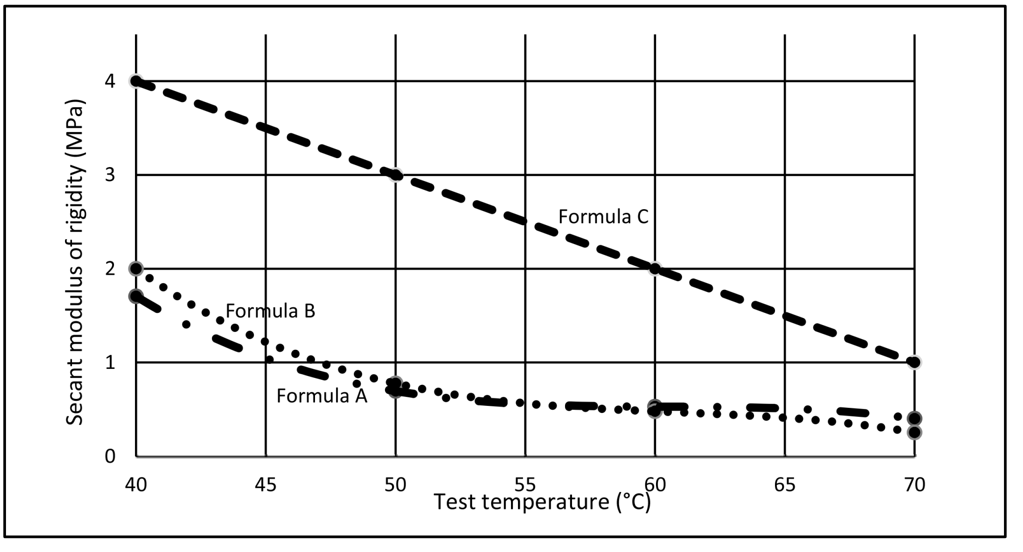

Figure 2. Evolution of secant moduli of stiffness of asphalt pavement surfaces as a function of temperature.

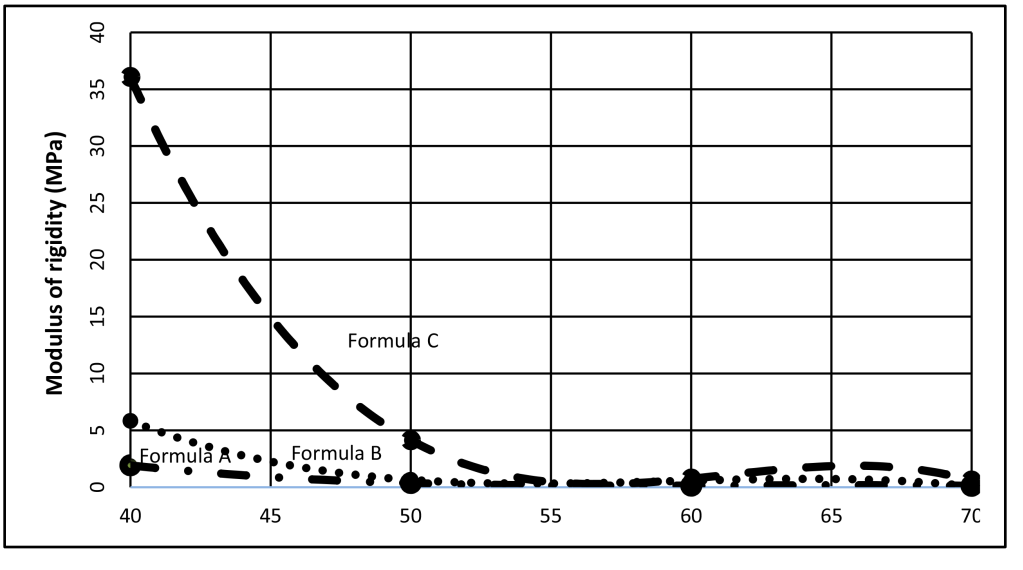

Figure 3. Evolution of stiffness moduli of asphalt pavement surfaces as a function of temperature, obtained from the semi-empirical approach.

with 50/70 bitumen are lower than those formulated with 35/50 and 10/65 bitumen. Thus, the higher the grade of bitumen, the higher the modulus of stiffness. Comparison of the results obtained from the two approaches used reveals that the modulus values are close with a root mean square deviation from the mean of between 6.58% and 14.8% (**Table 6**). However, the obtained dependencies of the stiffness moduli on temperature are given in **Table 7**.

Table 6. Mean stiffness moduli of asphalt mixes with root mean square (RMS) deviations between the two determination methods. (a) using the semi-empirical methodology; (b) results of the axial compression tests.

Temperature (˚C)	$\left\|E^*_{\text{formula A}_{(a)}}\right\|(\text{MPa})$	$\left\|E^*_{\text{formula A}_{(b)}}\right\|(\text{MPa})$	RMS
40	1.92	1.71	1.48×10^{-1}
50	3.62×10^{-1}	6.92×10^{-1}	2.36×10^{-1}
60	1.38×10^{-1}	5.29×10^{-1}	2.76×10^{-1}
70	1.19×10^{-1}	4×10^{-1}	1.99×10^{-1}

Temperature (˚C)	$\left\|E^*_{\text{formula B}_{(a)}}\right\|(\text{MPa})$	$\left\|E^*_{\text{formula B}_{(b)}}\right\|(\text{MPa})$	RMS
40	6.44	2.00	3.14
50	6.83×10^{-1}	7.76×10^{-1}	6.58×10^{-2}
60	6.01×10^{-1}	4.79×10^{-1}	8.63×10^{-2}
70	8.52×10^{-2}	2.54×10^{-1}	1.19×10^{-1}

Temperature (˚C)	$\left\|E^*_{\text{formula C}_{(a)}}\right\|(\text{MPa})$	$\left\|E^*_{\text{formula C}_{(b)}}\right\|(\text{MPa})$	RMS
40	3.61×10^{1}	4.00	2.27×10^{1}
50	4.13	3.00	7.99×10^{-1}
60	7.57×10^{-1}	2.00	8.79×10^{-1}
70	5.83×10^{-1}	1.00	2.95×10^{-1}

Table 7. Thermal dependence laws for stiffness moduli of asphalt mixes at 10 Hz.

Formula	Dependency law $\left\|E^*(T)\right\|$ at 10 Hz	
	Semi-experimental method	Axial compression method
A	$0.1883T^3 + 34.934T^2 + 2151.3T + 4\times10^7$ $R^2 = 1$	$4214.4T^2 - 480288T + 10^7$ $R^2 = 0.99$
B	$4.2266T^3 + 776.81T^2 - 47325T + 956663$ $R^2 = 1$	$-100000T + 810^6$ $R^2 = 1$
C	$1.0181T^2 - 181.09T + 208384$ $R^2 = 1$	$2592.2T^2 - 337821T + 10^7$ $R^2 = 0.98$

4. Conclusions and Perspectives

In this paper, temperature dependence laws for complex moduli of asphalt mixes were experimentally determined at test temperatures between 40˚C and 70˚C, the upper bound of which is quite close to actual temperatures (62˚C) of pavement surfaces during heat waves. The accuracy of the results was tested using the Heukelom and Klomp relationship which gives similar values for the complex moduli of asphalt mixes. The methodology presented in this paper therefore dispenses with the complex and expensive test for the determination of the complex modulus in order to gain a scientifically acceptable insight into the behaviour of asphalt mixes in the temperature range between 40˚C and 70˚C. Indeed, we have shown that the secant modulus of axial compression under these temperature and frequency conditions is equivalent to the complex modulus of the asphalt mix.

Consequently, the temperature dependence laws of the moduli could be used for a better local design of bituminous pavements because these moduli are representative of the hot weather conditions of the Burkinabe climate.

The results obtained could be used for design purposes or to study the thermomechanical behaviour of pavements under hot weather conditions.

Furthermore, a comparison of the evolution laws of the complex moduli obtained by the proposed semi-empirical method and those which could be obtained by fatigue tests on asphalt mixes is possible.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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