Behavior in stress and deformation of bituminous coating with modulus

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ABSTRACT: The importance of developing an analysis of the flexural behavior of beams is related firstly to the use of beams as a basic element in the realization of structures, and also to characterize the mechanical properties of laminates and sandwich materials from bending test performed on specimens shaped beams. Determining the mechanical behavior of pavement materials leads to calculate the distribution of stresses and strains in the pavement the rigidity of the materials, in order to determine the thickness to set up according to the resistance of these materials to different damage mechanisms, depending on climate and traffic. Comparison of the mechanical behavior of materials allows making a selection of the type of materials and interventions based on their performance. In addition, knowledge of the mechanical behavior of materials permits to develop specifications based on the physical properties of these materials and selection criteria for the type of intervention based on a cost analysis of the life cycle. This study examines the mechanical behavior of a quasi-compact bituminous material. It aims to develop a behavioral model which meets the requirements for industrial exploitation. Experimental responses show a behavior similar to that of concrete, namely the asymmetrical character (difference between tension and compression). Only the normal stress is taken into account, although for different layers, the normal distribution of the stress is linear and is based only on the depth of the beam. However, the stress distribution in the beam is not perfectly linear but piecewise linear.

Keywords: Stress, Strain, Stiffness, Bituminous Material, Piecewise Linear.

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1. Introduction
In recent years, road transportation, both for passengers and freight, have grown significantly with the result that traffic is much faster and more secure traffic. Many researchers have been conducted as to improve the limit speed used to design modern highways to respond to actual vehicle speeds which are increased very quickly. Variability of the mechanical properties of pavement materials is considered to be maintained within relatively narrow for materials developed and implemented in accordance with the standards and guidelines, the only factors taken into consideration to account for the variability in the appearance and development of pavement deterioration are the dispersions on: the results of fatigue tests and the thickness of the layers at runtime realization time [1, 2, 3, 4, 5]. The use of modified bitumen or upgraded for this project is justified by the following three main reasons:
- The modified bitumen is widely used with excelled results and I well decremented
- The modified bitumen are recommended for highways with high traffic and impolite axle loads because they increase the resistance to rutting and cracking while providing a better resistance to aggressive weather conditions (precipitation and temperatures).
- The use of modified bitumen reduces the cost of maintaining and operating at long term because of the high performance and extending life they give to the pavements. This last point is extremely important for the administration as the management costs of highways at long term can be very exorbitant if proper techniques are not used.

2. Characterization of mechanical properties of asphalt
In the literature the bituminous mixtures are considered as homogeneous materials, isotropic, visco-elastic, linear and thermo-sensitive. Ever thing, the rut is well characterized when considering an élasto-visco-plastic model for the asphalt concrete for lag deformation; high desperations and show coating. However the introduction of layers of asphalt creates a density gradient with depth after compaction, and directs a privileged aggregate. In addition the work of show that testing tension / compression on cylindrical specimens cored using different orientations, show differences of 20% on the results of a sample orientation to another [6, 7]. Therefore the samples are taken to heart the material to be found in conditions close to the assumption of isotropy. Laboratory and is therefore trying to make withdrawals and impose stresses that correspond to the direction of greater distortion. The modulus measurements of bituminous materials are used in their linear range. This therefore requires application of "small deformations" [8, 9]. The assumption of a linear viscoelastic behavior of asphalt is accompanied by the validity of the Boltzmann superposition principle [10]: the response of a material to a request made by a number of requests is the sum of elementary responses to each of these basic demands [11].

3. Stresses and strains within the structure
The mechanical strength of asphalt concrete in tension is less than one tenth of that in compression. Different types of tests can be done to characterize the behavior of the material under tension. However, this technique is heavy to set up and requires specific equipment.
The level of normal strain in the layer can be different depending on the location of the neutral surface of the beam. The neutral surface is the surface where strain/stress is zero. The strains/stresses below the neutral surface and above the neutral surface have
opposite signs (Figure 1). In pure bending, the normal strain ($\varepsilon_x$) and stress ($\sigma_x$) in x-direction can be expressed as, respectively,

$$\sigma_x = E_i \varepsilon_x = -E_i \kappa z$$  \hspace{1cm} (1)
$$\varepsilon_x = -\frac{z}{R} = \kappa z$$  \hspace{1cm} (2)

Where \( \kappa = \frac{1}{R} \) is the curvature of the beam due to bending, R is the radius of curvature, \( E_i \) is the Young’s modulus, and \( z \) is the distance on Z-coordinate from the neutral surface. For small deflections of the beam compared to its length of the beam, the radius of curvature can be determined from the following equation (assume the beam is under pure bending).

$$D_x (x, t) = z \frac{\partial w(x, t)}{\partial x}$$ \hspace{1cm} (3)
$$D_y (x, t) = 0 \quad \text{and} \quad D_z (x, z, t) = w(x, t))$$ \hspace{1cm} (4)

$$1 \frac{1}{R} = \left[ 1 + \left( \frac{\partial^2 w(x, t)}{\partial x^2} \right) \right]^{3/2}$$ \hspace{1cm} (5)

If the beam is slightly bent, then \( \frac{\partial^2 w(x, t)}{\partial x^2} \ll 1 \), Equation (5) can be approximated as:

$$\kappa = \frac{1}{R} = -\frac{\partial^2 w(x, t)}{\partial x^2} = -\frac{\partial w(x, y, t)}{\partial y} = -\frac{M}{E_i l}$$ \hspace{1cm} (6)

where

$$M = -\int_S z \sigma_x dS = -\kappa E \int_S z^2 dS = -\kappa E_i l$$ \hspace{1cm} (7)

and \( l = \int_S z^2 dS \) \hspace{1cm} (8)

4. Numerical studies

Asphalt Concrete with high modulus (BBME 1) in surface layer;
Material with high modulus (EME 2) for the base and foundation layers.

The use of BBME 1 and EME2 respectively for surface layers and base layers aims to improve the rutting resistance of the binder for the BBME and resistance to fatigue of
the base and foundation layers for the EME. According to past experiences, an asphalt of great rigidity with high modules can be achieved by using hard bitumen, a modified bitumen, or the addition of additive in order to increase the modules. The use of modified bitumen or pure bitumen with additives, and although it increases the initial cost of construction of the road, will be used to significantly reduce maintenance costs of the road in long term, because the duration of service of the roadway is increased. The hard coated is usually formed of 10/30 bitumen with proven performance in Europe. However the supply of 10/30 bitumen is deficient in any project area, therefore, it is unrealistic to use the 10/30 bitumen for some countries. Nevertheless, we can achieve the performance of bitumen 10/30 with 35/50 by adding a suitable additive [12, 13].

The technique of asphalt with high modules is already old and the first use on the road dating back some thirty years. But over the last ten years the use is developing rapidly in some countries, which use them for a significant proportion of maintenance pavement surface with heavy traffic, sometimes they are imposed in- beyond a certain level of traffic as the case of the Algerian East-West Highway. Other countries are on the contrary very reserved.

5. The average normal strain

From Equation (1) and Equation (6), the normal strain along the x-coordinate can be calculated as:

$$\varepsilon_x = -\frac{z}{R} = -\frac{Mz}{E I} \quad (9)$$

For the BBME layer, the strain in its middle surface (centroid) is

$$\varepsilon_{bbme} = \frac{M(z_{bbme} - \bar{z})}{E_{eme} I_{eme} + E_{bbme} I_{bbme}} = \frac{M(\bar{z} - z_{bbme})}{E_{eme} I_{eme} + E_{bbme} I_{bbme}}$$

$$= \left(\frac{b h_{eme}^3}{12} + (\bar{z} - z_{eme})^2 b h_{eme} + n \left(\frac{b h_{eme}^3}{12} + (\bar{z} - z_{bbme})^2 b h_{bbme}\right)\right)$$

$$= \left(\frac{M}{E_{eme}}\right) \frac{b h_{eme}^3}{12} + (\bar{z} - z_{eme})^2 b h_{eme} + n \left(\frac{b h_{eme}^3}{12} + (\bar{z} - z_{bbme})^2 b h_{bbme}\right)$$

(10)

With

- z is the distance from neutral surface,
- $\mu = \frac{h_{bbme}}{h_{eme}}$: Young’s modulus ratio of BBME over EME2,
- $n = \frac{E_{bbme}}{E_{eme}}$: Thickness ratio of BBME over EME2.

From the following equations (11 and 12),

$$\bar{z} - z_{bbme} = h_{bbme} E_{bbme} z_{bbme} + h_{eme} E_{eme} z_{eme} - z_{bbme}$$

$$= \frac{h_{eme} E_{eme} (z_{eme} - z_{bbme})}{h_{bbme} E_{bbme} + h_{eme} E_{eme}} = \frac{h_{bbme} E_{bbme} (h_{bbme} + h_{eme})}{2(h_{bbme} E_{bbme} + h_{eme} E_{eme})} = \frac{h_{bbme} (1 + \mu)}{2(1 + \mu n)} \quad (11)$$

$$\bar{z} - z_{eme} = \frac{h_{eme} E_{eme} (z_{eme} - z_{bbme})}{h_{bbme} E_{bbme} + h_{eme} E_{eme}} = \frac{h_{bbme} E_{bbme} (h_{bbme} + h_{eme})}{2(h_{bbme} E_{bbme} + h_{eme} E_{eme})}$$

$$= \frac{h_{eme} E_{eme} (z_{eme} - h_{bbme} E_{bbme} z_{bbme})}{h_{bbme} E_{bbme} + h_{eme} E_{eme}} = \frac{h_{bbme} E_{bbme} (h_{bbme} + h_{eme})}{2(h_{bbme} E_{bbme} + h_{eme} E_{eme})}$$

$$= \frac{h_{eme} E_{eme} (z_{eme} - h_{eme} E_{eme})}{h_{bbme} E_{bbme} E_{eme}} = \frac{h_{bbme} E_{bbme} (h_{bbme} + h_{eme})}{2(h_{bbme} E_{bbme} + h_{eme} E_{eme})}$$

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The equation (12) becomes:

\[
\varepsilon_{bbme} = \frac{\mu n}{2(1 + \mu n)} h_{bbme} (1 + \mu)
\]

The equation (10) becomes:

\[
(e_{bbme})_{toy} = \left(\frac{6M}{b h_{eme}^2 E_{eme}}\right) \frac{\mu + 1}{\mu^4 n^2 + (4\mu^3 + 6\mu^2 + 4\mu)n + 1} h_{eme} (1 + \mu)
\]

\[
= \left(\frac{M}{b E_{eme}}\right) \frac{h_{eme}^3 + nh_{bbme}^3}{12} + h_{eme} \left(-\mu n h_{eme} (1 + \mu)\right)^2 + nh_{bbme} \left(h_{eme} (1 + \mu)\right)^2
\]

\[
= \left(\frac{M}{b h_{eme}^2 E_{eme}}\right) \frac{1 + \eta \mu^3}{12} + (\mu^2 n^2 + n\mu) \left(\frac{1 + \mu}{2(1 + \mu n)}\right)^2
\]

The plot of the average strain in the BBME with four different thickness ratios is shown in Figure 2. The Young’s modulus of the EME2 and bending moment used in the simulation are \(E_{eme} = 11\) (GPa) and \(M = 100\) (N-m) respectively.

**Figure 2: Average strain of the BBME layer (on the middle surface of the BBME)**

For the surface layer, we have the same configuration (deformation, modulus of rigidity) for the different thickness ratios.

We note that for high rigidity \(n\), the deformations become small which means that if the modules of rigidity of the surface layer are more important than that of the base layer, we should have a better distribution of the load due to traffic towards the main part of the roadway, so a small deformation of bitumen layers.
Therefore, for greater thickness of the base layer the deformation of the surface layer (BBME) becomes more important which confirms that the thickness ratio has an influence on the deformation behavior of the pavement.

Similarly, for the base layer, the strain in the middle surface (centeroid) of the EME is

\[
\left(\varepsilon_{eme}\right)_{moy} = -\frac{M(z_{eme} - \bar{z})}{E_{eme}I_{eme} + E_{bbme}I_{bbme}} = \frac{M(\bar{z} - z_{eme})}{\bar{z} - z_{eme}}
\]

\[
= \left(\frac{M}{E_{eme}}\right)\frac{bh_{eme}^3}{12} + \frac{1}{2} b h_{eme} + n \left(\frac{bh_{bbme}^3}{12} + (\bar{z} - z_{bbme})^2 b h_{bbme}\right)
\]

\[
= \left(\frac{M}{bE_{eme}}\right)\frac{h_{eme}^3 + nh_{bbme}^3}{12} + h_{eme} \left(-\frac{\mu n h_{eme} (1 + \mu)}{2(1 + \mu n)}\right)^2 + \mu h_{bbme} \left(\frac{h_{eme} (1 + \mu)}{2(1 + \mu n)}\right)^2
\]

\[
= \left(\frac{-M}{b h_{eme}^3 E_{eme}}\right)\frac{1 + n\mu^2}{12} + (\mu^2 + \mu) n \left(\frac{1 + \mu}{2(1 + \mu n)}\right)^2
\]

\[
= \left(\frac{-6M}{b h_{eme}^2 E_{eme}}\right)\mu n^2 + (4\mu^3 + 6\mu^2 + 4\mu) n + 1
\]

The average deformation in the base layer (EME2) for four different thickness ratios is represented in figure 3.

![Figure 3: Average strain of the EME2 layer (on the middle surface of the EME2)](image)
For the base layer, we have a distribution with opposite sign which means that the deformation transmitted from the surface layer is balanced at the base layer level. This is the bought objective from the base layer. In addition, if the thickness of the surface layer is between 0.5 and 1 the base layer thickness we have a homogeneous and uniform distribution for different rigidity ratios.

Otherwise, if the thickness of the surface layer is small compared to the thickness of the base layer, we have a change of sign of deformation in the EME2 layer, which means that the distributer of effort between the surface and base layers is very important. Figures 2 and 3 show that the deformations in the base and surface layers have opposite signs, and when “n” is not too large, the average strain at the surface layer is much greater than that of the base layer.

The interface surface layer -base layer is also a sensitive area because it is often subjected to high normal stresses and horizontal shear and the upper centimeters of the treated seat present often low resistance represented in the following figure.

6. Average normal stresses
The stress \( \sigma \) can be obtained from equation \( \sigma = E_i \varepsilon \), where \( E_i \) is the Young’s modulus. The average stress of the BBME layer is

\[
(\sigma_{bbme})_{moy} = E_{bbme} (\varepsilon_{bbme})_{moy} = nE_{eme} (\varepsilon_{bbme})_{moy} = \left( \frac{6M}{bh_{eme}^2} \right) \mu n + \frac{1}{n + 1}
\]

The average stress of the EME layer

\[
(\sigma_{eme})_{moy} = E_{eme} (\varepsilon_{eme})_{moy} = \frac{-6M}{bh_{eme}^2} \frac{\mu n + 1}{\mu n + \frac{1}{n + 1}}
\]

One can notice that the ratio of average stress in the base layer over that of surface base average stress in the is equal to the thickness ratio \( \mu \) but in opposite sign \( -\mu \), i.e.

\[
(\sigma_{eme})_{moy} = -\mu
\]

When \( \mu = 1 \), the average stresses in the EME2 and the BBME are the same but with negative sign.

Figures 4 and 5 are the plots of the average stresses in the BBME and the EME2 respectively.
Figure 4 shows that the stress distribution at the surface layer is uniform for low thickness ratios, otherwise if the thickness ratio between the layers exceeds 0,5 we have
no distribution stress. This confirms the results in Figure 5 for the strain distribution in
the base layer....

Figure 5 shows the same distribution obtained in Figure 3, so we have linear distribution
of behavior between the stresses and strains at the base layer which means that the base
layer provide to roadway mechanical strength to vertical loads induced by traffic and
distribute the pressure on the support platform to maintain the deformation to an
acceptable level.

The amplitude of the extension part of the signal solicitation is approximately three to
four times greater than that corresponding to the part in contraction. In addition, the
resistance of the asphalt in tension is much lower than its compressive strength. The
fatigue damage is therefore mainly in the phase of traction. Traction by bending being
greater at the base of the roadway, the beginning of the crack should theoretically
trigger there.
The shape of the load and the number of parameters that define it (change in
temperature, load, traffic, layer thickness, and the bearing capacity of foundation soil,
climatic effects, modulus of rigidity ...) highlight the difficulties of reproducing the
actual load.

7. Conclusion
Stresses and displacements transmission between the base and surface layers depend
mainly a mechanical behavior of the two layers and also behaviors of the tree layers at
the interface.
From the structural point of view, it is as essential information for pavement design.
If used on support layers in good structural condition, the asphalt with high modulus
show no damage due to fatigue due to the balance between the strain distribution
between the base and surface layer (2, 3), and to the distribution of stress at these two
layers (Figure. 4 and 5).

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