Shear strength of hot-mix asphalt and its relation to near-surface pavement failure – A case study in Southern Brazil

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ABSTRACT

Since the years 1970, several design methods of flexible pavements have considered fatigue bottom-up cracking as the most critical degradation mechanism. However, in recent times, premature distresses originated close to the surface of pavements, especially in those with thick asphalt layers. These distresses are cracks initiating close to the surface and rutting, which are considered as shear failures. Shear failure close to the pavement surface is a complex phenomenon caused by factors like: tire-pavement shear stresses, asphalt characteristics and environmental conditions. In this article, besides discussing theoretical aspects related, the behavior of asphalt is characterized by shear strength tests and risk analysis of failure close to the pavement surface. It was found that bitumen modification with SBS remarkably increases cohesion and, consequently, the asphalt shear strength. While the shear strength parameters for asphalt with conventional bitumen, at 25°C, are: c = 480 kPa and angle of internal friction angle(fi) = 46°, the tests on asphalt with SBS modified bitumen, also at 25°C, resulted in c = 1,006 kPa andfi = 40°. Regarding SBS modified asphalt, the increase of test temperature from 25°C to 40°c significantly reduces the cohesive interception from 1,006 kPa to 722 kPa, while the friction angle, which is a function of aggregates internal friction and interlocking, remains the same (40°). The risk of shear failure near surface of a pavement consisting of 8.0 cm of SBS modified asphalt; 45.0 cm of crushed rock layers and 60.0 cm of sand was evaluated. The non-uniformity of contact stresses was taken into account using software EverStress FE. In spite of the structure being safe against shear failure (due to the SBS modified bitumen high cohesion), it was shown that considering the thermal gradient on critical shear stresses computations is of paramount importance in the case of overloading.

Keywords: Asphalt, Cohesion, Friction, Polymers

1. INTRODUCTION

Since the years 1970, most of design methods of flexible pavements have considered fatigue bottom-up cracking as the most critical degradation mechanism. However, in recent times, premature distresses originated close to the surface of pavements, especially in those with thick asphalt layers. These distresses are: cracks initiating close to the surface and rutting, which are considered as shear failures.

Rutting, one of the most important failure distresses caused by heavy loads on asphalt pavements, is related to shear strains in the asphalt layer. Top-down cracking (TDC), generally in the longitudinal direction, has become a more common distress in recent years and may also be considered as shear failure.

In order to analyze the risk of shear failure in the asphalt layer, the shear strength parameters of asphalt must be measured in laboratory tests and shear stresses acting close to pavement surface must be computed. Hence, the objectives of the research reported in this paper were: a) to present shear strength parameters of asphalts with conventional and polymer modified bitumen commonly used in Brazil; b) to analyze the influence of pavement temperature on asphalt shear strength parameters and c) to evaluate the risk of near-surface pavement failures.

2. OVERVIEW

According to Wang & Al-Qadi [1], near-surface failure is a complex phenomenon that results from various factors such as tire-pressure contact stress, asphalt characteristics, pavement structural design, and environmental conditions.

Most conventional flexible pavement design methods assume simplified loading (circular and stationary, inflation pressure equal to contact stress), elastic materials properties of asphalt, and full-bonded layer interface. However, as pointed out by Wang & Al-Qadi [1], these assumptions are inconsistent with realistic truck tire loading conditions and may result in erroneous pavement response calculation and pavement performance prediction, especially at the pavement near-surface, where the effect of tire-pavement interaction is significant.

Myers et al. [2], Drakos et al. [3] and Wang & Al-Qadi [1] report that the tensile or shear stress-strain near the pavement surface caused by tire-pavement interfacial contact stresses is one of the main factors causing near-surface pavement failure. Truck tires produce highly nonuniform vertical contact stresses under each tire rib and under the tire edges, creating a complex 3-D stress state near the pavement's surface. So, instead of considering only one-dimensional tensile or shear stress-strain, the multiaxial stress state needs to be considered when the material failure potential is analyzed at pavement near-surface.

Since the early 1990s, researches carried out in South Africa using a 3-D stress cell [4] have shown that vertical contact stresses are not uniform. To illustrate this non-uniformity, in Figure 1 the vertical contact stresses across a single truck tire 11R22.5 are shown. The figure indicates three test conditions of loading (18 kN, 30 kN and 49 kN) at constant inflation pressure of 620 kPa.

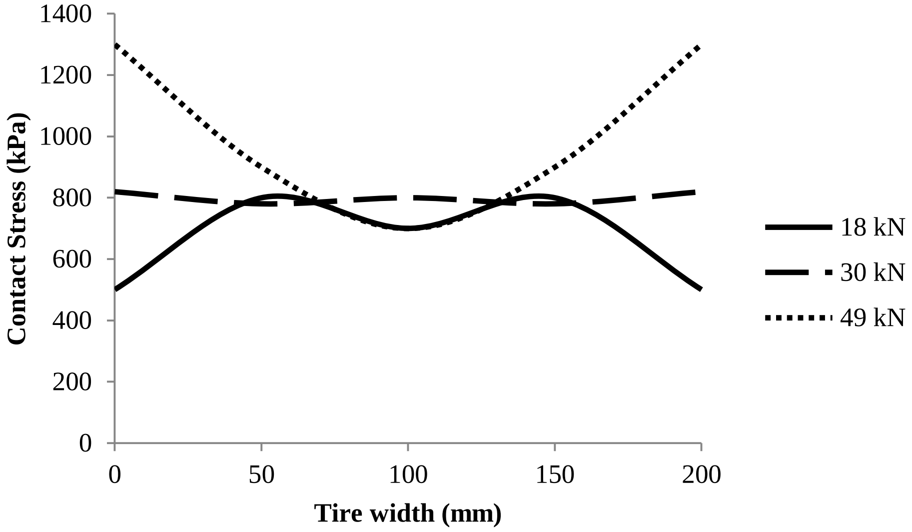


Figure 1: Vertical contact stresses across the tire width for different tire loads at constant inflation pressure of 620 kPa. Adapted from De Beer et al. [4]

For the 18 kN tire load the vertical stress distribution appears to be relatively uniform concave bulge, but for tire loads of 30 kN and 49 kN (over-loading and extreme overloading), bulging of the tire walls occurs and it is clear that the tire load is transferred to the tire edges, attaining values as high as 1,300 kPa (more than twice the inflation pressure).

Su et al. [5] evaluated the shear stresses caused by non-uniform vertical contact stresses in asphalt layers and found out that in case of overloading (tire load of 50 kN and inflation pressure of 810 kPa) the larger shear stresses (370 kPa) are, similarly, focused at the tire edge. Consequently, a shear plane may develop near the tire edge if the shear stress is high enough, forcing the asphalt away from the tire. According to the authors, this might be the mechanism responsible for shear deformation (rutting) and the formation of TDC.

Wang & Al-Qadi [1] consider that since the asphalts are composed of aggregates, water and air, they are analogous to soils composed by solids, water and air. So, at intermediate temperatures, asphalt may be modeled as Mohr-Coulomb materials with both cohesive and granular properties.

As pointed out by Wang & Al-Qadi [1], the Mohr-Coulomb theory provides an easy way to express the multiaxial stress state by using Mohr's circles, such as shown in Figure 2. The Mohr's circle is plotted at center $(\sigma_1 + \sigma_3)/2$ and has radius of $(\sigma_1 - \sigma_3)/2$, where σ_1 and σ_3 are the maximum and minimum principal stresses in a 2-D state of stress.

The Mohr-Coulomb failure envelope is defined by model (1), where τ is the shear stress at failure (shear strength), σ is the normal stress at failure, *c* is the cohesive interception and ϕ is the internal angle of friction. The shear strength parameters (*c* and ϕ) are normally based on triaxial tests carried out at different confinement levels, as shown in Figure 3.

$$\tau = c + \sigma \tan \phi \qquad (1)$$

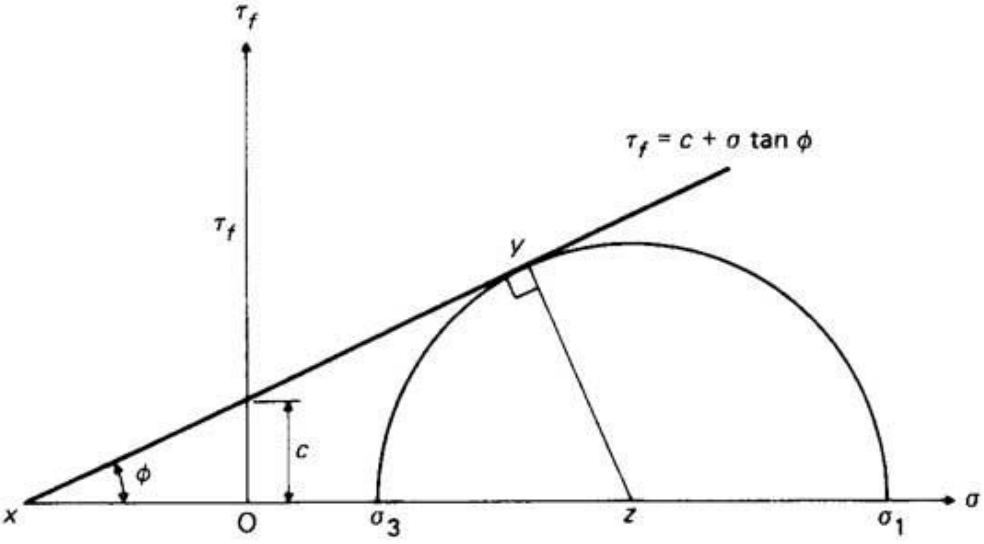


Figure 2: Mohr's circle and Mohr-Coulomb failure criterion

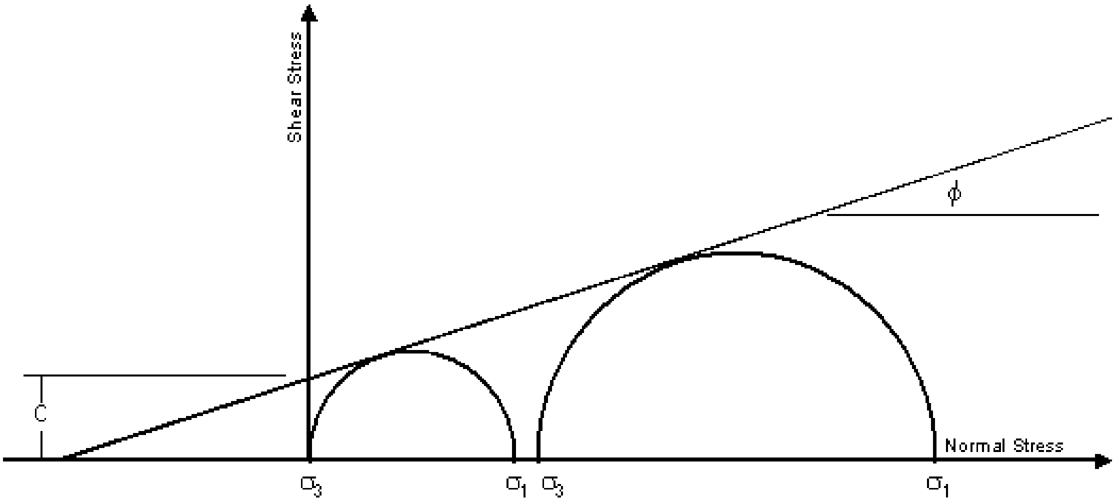


Figure 3: Mohr-Coulomb failure criterion drawn based on two tests

According to Tan et al. [6], the friction angle of asphalt is largely a function of interlocking and the aggregate friction and is independent of test temperatures, while the cohesive interception of asphalt is governed by the bitumen properties and highly depends on test temperature and strain rate. Novak et al. [7] added that at elevated temperatures, asphalts behave like granular materials with little cohesion because the bitumen becomes less viscous.

In order to evaluate the pavement failure potential at near-surface under trucks loading, Wang & Al-Qadi [1], based on results reported by Gokhale et al. [8] and Hajj et al. [9], assumed as strength parameters of asphalts a friction angle of 40° and cohesion of 400 kPa at 45°C and 600 kPa at 25°C. In Brazil, Núñez et al. [10], based on the results of triaxial tests, reported the following shear strength parameters at 25°C for asphalts with conventional bitumen (50/60 x 10^{-1} mm penetration): c = 480 kPa and ϕ = 46°.

3. EXPERIMENTAL PROCEDURES AND ASPHALTS COMPOSITIONS

With the purpose of obtaining the shear strength parameters (friction angle, ϕ, and cohesion, c) of polymer modified asphalts used in southern Brazil, triaxial shear strength tests , with confining stresses of 50 kPa, 100 KPa and 200 kPa, were carried following ASTM D2664 standard [11]. Cylindrical specimens (5 cm x 10 cm) of asphalts with SBS modified bitumen (softening point of 60°C and elastic recovery of 85%) were compacted in laboratory.

Conventional bitumen specimens were tested only at 25°C, while the polymer modified bitumen specimens were tested at 25°C and 40°C. Test results on specimens with the conventional bitumen have been previously reported by Núñez et al. [10], but they are also considered in this paper in order to allow comparisons regarding the effects of bitumen's properties on asphalt shear strength.

The grain size distributions of aggregates of asphalts with conventional or modified bitumen are shown in Table 1.

Bitumen contents were 4.2% for the conventional asphalt and 4.7% for the polymer modified asphalt. Air voids in the conventional and in the modified asphalts were, respectively, 4.2% and 4.7%. The voids in the mineral aggregates (VMA) were 16% in the modified asphalt and 12.4% in the asphalt with conventional bitumen.

Table 1: Aggregates grain size distribution for both asphalts

Sieve	**Percent finer**	
	Asphalt with conventional bitumen	**Asphalt with polymer modified bitumen**
1"		100
3/4"	100	99.1
1/2"	91.5	78.2
3/8"	82.6	66.2
N 4	55.3	34.5
Nº 10	37.8	21.3
Nº 40	15.9	11.5
Nº 80	10.3	8.8
Nº 200	6.9	5.6

4. TESTS RESULTS AND ANALYSIS

The asphalts stress-strain behavior followed a pattern shown in Figure 4; increase of axial stress with axial strain at a constant rate up to a peak, followed by a ductile behavior.

The effect of test temperature is clearly seen in Figure 4; a sharp decrease of axial stress (from 5,500 to 3,500 kPa) and a marked increase in the corresponding axial strain (from 0.3 % to 0.5%). In both cases the stress after peak is practically invariable. As expected, at higher temperature the specimen becomes less resistant and more ductile; that is, the deformation modulus decreases.

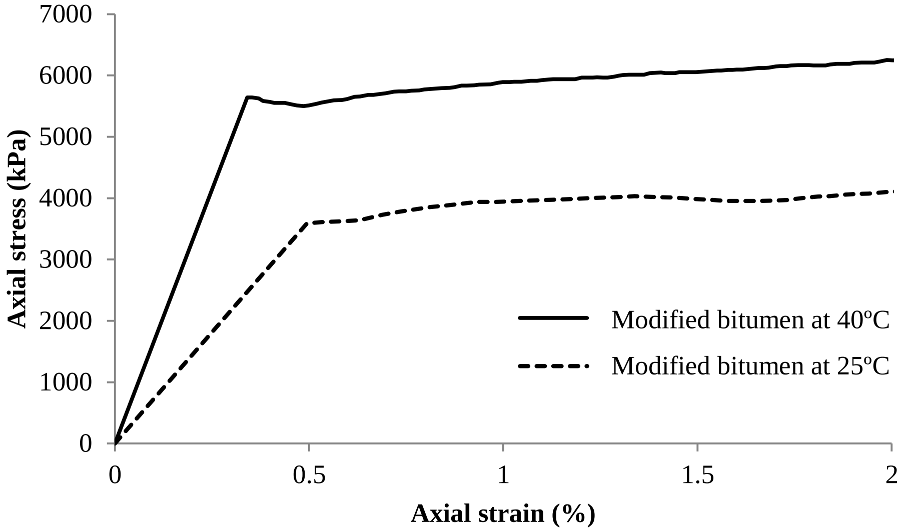


Figure 4: Typical strain-stress behavior and effect of test temperature on asphalt with modified bitumen (Confining pressure of 200 kPa)

In order to evaluate the effects of bitumen modifying on asphalts shear strength, in Figure 5 Mohr-Coulomb envelopes for both types of asphalt are shown. As expected, modifying the asphalt bitumen led to higher cohesion values and, consequently, higher shear strength.

As previously stated, the shear strength parameters for the asphalt with conventional bitumen tested by Núñez et al. [10], at 25°C, are: c = 480 kPa and ϕ = 46°. On the other hand, tests on asphalt with SBS modified bitumen, also at 25°C, resulted in c = 1,006 kPa and ϕ = 40°. That is, the use of modified bitumen increased the asphalt cohesion in more than 100%, while the friction angle slightly decreased. The decrease in ϕ value may be due to the different grain size distributions, which result in different interlocking level; but it may be also partly due to the process of fitting Mohr's circles failure envelope. Nevertheless, the friction angles, ϕ, of both asphalts tested for this paper are quite close (or identical) to the value (40°) considered by Wang & Al-Qadi [1] as representative of asphalts produced in the US.

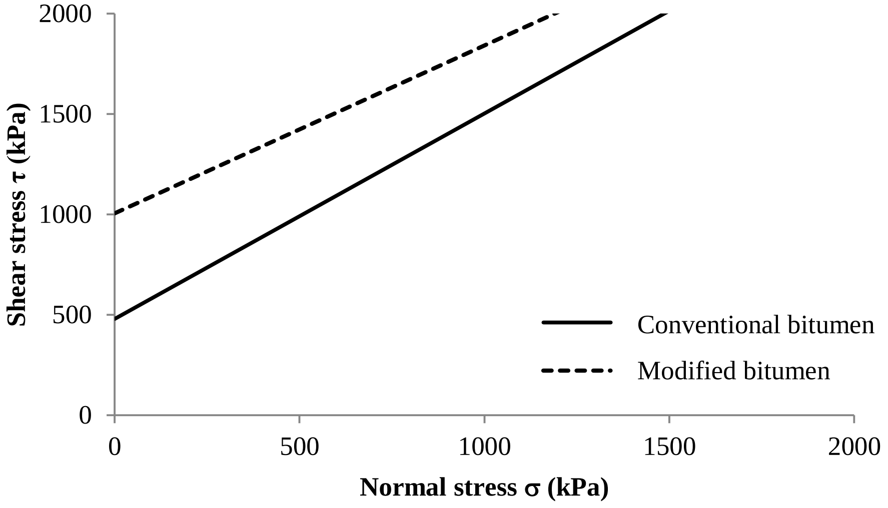


Figure 5: Mohr-Coulomb failure envelopes for asphalts with conventional or modified bitumen (Specimens tested at 25°C)

In sunny summer days, in Southern Brazil, pavement temperatures frequently attain 40°C, or even more. It is show in Figure 6 that the increase of test temperature from 25°C to 40°c significantly reduces the cohesive interception from 1,006 kPa to 722 kPa, while the friction angle remains the same (40°).

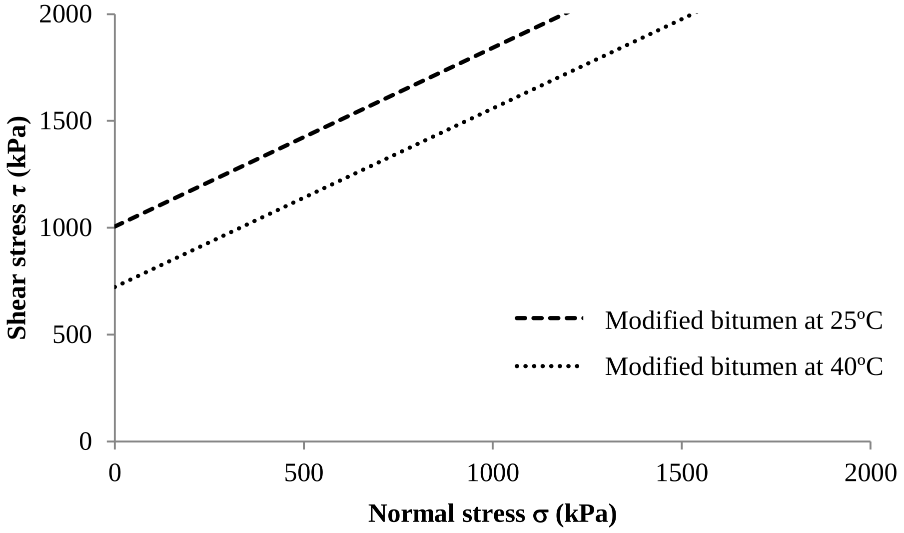


Figure 6: Effect of test temperature on the shear strength of asphalt with modified bitumen

The cohesion drop of nearly 28% when temperature rises from 25 to 40°C, shown in Figure 6, is similar to the value considered by Wang & Al-Qadi [1], which is 33% (from 600 kPa to 400 kPa).

5. EVALUATION OF RISK OF NEAR-SURFACE PAVEMENTS FAILURE

Considering the shear strength parameters for the asphalt with modified bitumen at temperatures of 25°C and 40°C, we evaluate in this section the risk of near-surface pavement shear failure.

Initially we remember that Su et al. [5] and Wang & Al-Qadi [1] numerically evaluated the effects of non-uniform contact stresses on the shear stress acting on pavements. Su et al. [5] concluded that the larger shear stresses are focused at the tire edge in the case of overloading (high tire load/tire pressure ratio). Wang & Al-Qadi [1] concluded that shear-induced cracking usually develops at a location with relative high shear stresses and low confinement. When confinement is low, those authors added, the importance of shear stresses in the formation and growth of near-surface cracking should not be neglected, and an asphalt that is sensitive to rutting at high temperatures may also be sensitive to shear-induced cracking.

So, at a first sight, the critical situation regarding shear failure is under the tire edge at surface or near it, where the confinement is inexistent, or very low, and shear strength depends solely on cohesion (since $\sigma = 0$, model 1 is reduced to $\tau = c$). The risk of failure near the surface increases at high temperatures when cohesion decreases.

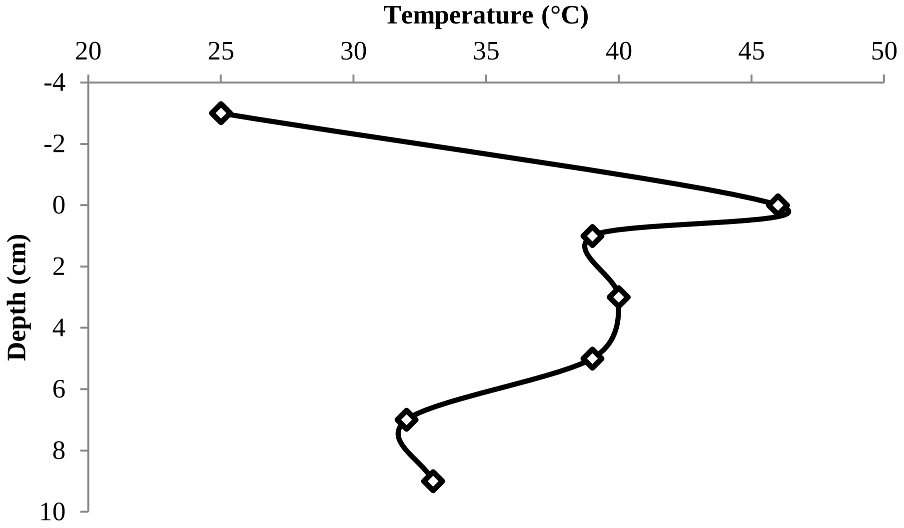
Pavements failure also depends on the acting shear stresses which, as previously seen, are highly influenced by the non-uniformity of tire-contact stresses. In order to take into account that non-uniformity Everstress FE software [12] was used to compute shear strains and stresses. EverStress FE version 1.0 is a 3D finite-element analysis tool for simulating the response of flexible pavement systems subjected to wheel loads. Some significant features of EverStress FE include the ability to model multiple-wheel systems with various tire contact patches and the ability to create user-defined loads with spatially varying tire contact pressures.

In a first analysis, we considered the following pavement, where the studied SBS modified asphalt has been used as wearing course: 8.0 cm-thick SBS modified asphalt; 15 cm-thick well-graded crushed rock base; 30 cm-thick dry macadam and 60 cm-thick sand over a clayey subgrade. Based on backanalysis, pavement layers resilient moduli mean values were assumed as 4,300 MPa for the SBS modified asphalt layer, at 25°C; 150 MPa for the granular layers and 60 MPa for the soil subgrade. Poison's ratios of 0.30 (asphalt); 0.35 (granular layers) and 0.45 (clayey subgrade) were considered.

As for the loading, the vertical contact stresses across the tire for the tire loads of 18.0; 30.0 and 49.0 kN, at constant inflation pressure of 620 kPa, shown in Figure 1 were adopted. Although 49.0 kN almost doubles the allowable tire load in Brazil (25.0 kN), tire loads even higher have been weighted in the freeway where the SBS modified asphalt has been used.

Considering 25°C as unique pavement temperature through the SBS modified asphalt layer (no thermal gradient) and using EverStress FE, the following critical shear stresses were computed: 225 kPa; 289kPa and 327 kPa for the tire loads of 18.0 kN; 30.0 kN and 49.0 kN, respectively. Even the higher critical shear stress (327 kPa) is much lower than the SBS modified asphalt cohesion at 25°C, 1,006 kPa, or at 40°C, that is, 722 kPa. Therefore, we may conclude that, under a no thermal gradient condition, the asphalt wearing course is safe against shear failure.

However, thermal gradient in a 8 cm-thick asphalt layer does occur. Throughout 18 months, Núñez et al. [13] recorded air temperatures, sun radiation and temperatures at the surface and at depths from 1.0 cm to 9.0 cm in an asphalt wearing course, in southern Brazil. It is shown in Figure 7 that in a sunny summer day, at 11.00 AM, when air temperature was 25°C; pavement temperature on the surface and in the first centimeter was 46°C; between 1.0 cm and 5.0 cm-deep pavement temperature was 40°C and between 5.0 cm and 8.0 cm the temperature was close to 33°C. Therefore, the resilient modulus of the wearing course varies with pavement depth and this must be taken into account when computing shear stresses.



Note: The temperature at the depth of -3.0 cm corresponds to air temperature.

Figure 7: Thermal gradient in a sunny summer day in southern Brazil [13]

The effect of temperature on the resilient modulus of the SBS modified asphalt analyzed in this paper is shown Figure 8 and the results are fitted by model (2).

$$RM = 9{,}750 - 203\ T \qquad (2)$$

where RM is the SBS modified asphalt resilient modulus (in MPa) and T is the specimens temperature during testing (in °C).

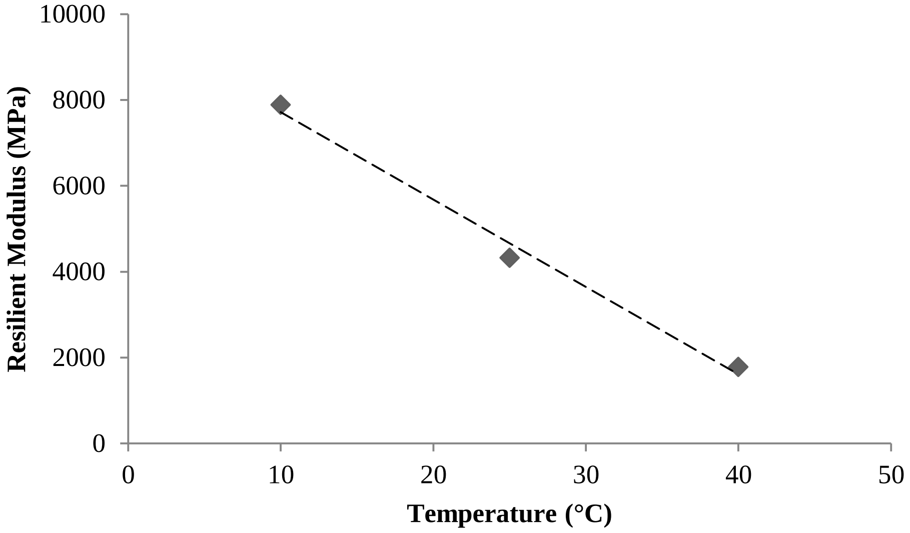


Figure 8: Effect of test temperature on the resilient modulus of the SBS modified asphalt

By using model (2) and considering the thermal gradient in Figure 7, the resilient moduli computed for the SBS modified asphalt are: from surface to 1.0 cm deep, RM = 394 MPa; from 1.0 to 5.0 cm deep, RM = 1,614 MPa and from 5.0 to 8.0 cm deep RM= 3,038 MPa.

Again, EverStress FE was used to compute shear stresses, but this time, dividing the asphalt wearing course in three layers (0 to 1.0 cm; 1.0 to 5.0 cm and 5.0 to 8.0 cm) with the corresponding resilient moduli. All other parameters (tire loads, inflation pressure, granular layers and soil subgrade characteristics) were kept the same.

Now, considering the thermal gradient, the following critical shear stresses were computed: 298 kPa; 428 kPa and 683 kPa for the tire loads of 18.0 kN; 30.0 kN and 49.0 kN, respectively. The higher critical shear stress (683 kPa) is still much lower than the SBS modified asphalt cohesion at 25°C, 1,006 kPa; but just a little higher than the cohesion at 40°C, 722 kPa. Although the SBS modified asphalt layer seems to be safe against shear failure, the importance of considering the thermal gradient is undisputable.

The critical shear stresses considering or not the thermal gradient are shown in Figure 9. It may be seen that considering the thermal gradient on critical shear stresses computations is of paramount importance in the case of overloading.

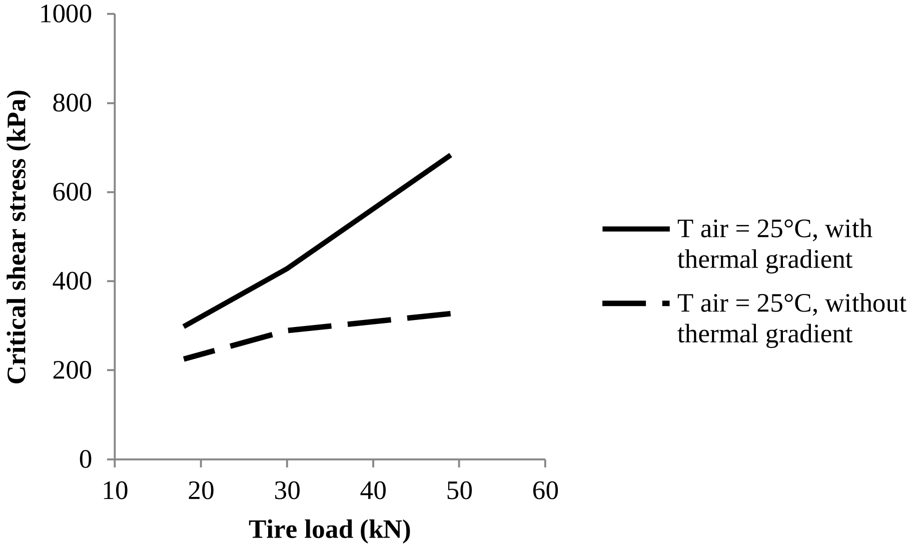


Figure 9: Critical shear stresses as a function of tire load, with or without thermal gradient (Tire inflation pressure of 620 kPa)

The performance of a pavement section with the structure considered in the previous analysis has been monitored since December 2010 and up to the moment of writing this paper (April 2014) no significant shear failure (top-down cracking or rutting) has been observed.

6. CONCLUSIONS

Based on test results on specimens of asphalt with conventional bitumen, previously reported by Núñez et al. [10], and new test results on SBS modified asphalt reported and analyzed in this paper we may conclude that:

- The Mohr-Coulomb criterion may be used to evaluate the risk of shear failure in asphalt layers.
- The SBS modified asphalt stress-strain behavior follows a pattern characterized by increase of axial stress with axial strain at a constant rate up to a peak, followed by a ductile behavior.
- The effect of bitumen's properties in asphalt shear strength may be clearly seen. Bitumen modification with SBS remarkably increases cohesion and, consequently, the asphalt shear strength. While the shear strength parameters for the asphalt with conventional bitumen, at 25°C, are: c = 480 kPa and ϕ = 46°, the tests on asphalt with SBS modified bitumen, also at 25°C, resulted in c = 1,006 kPa and ϕ = 40°.
- Regarding SBS modified asphalt, the increase of test temperature from 25°C to 40°c significantly reduces the cohesive interception from 1,006 kPa to 722 kPa, while the friction angle, which is a function of aggregates internal friction and interlocking, remains the same (40°).
- The risk of shear failure near surface of a pavement consisting of 8.0 cm of SBS modified asphalt; 45.0 cm of crushed rock layers and 60.0 cm of sand was evaluated. The non-uniformity of contact stresses was taken into account using software EverStress FE. In spite of the structure being safe against shear failure (due to the SBS modified bitumen high cohesion), it was shown that considering the thermal gradient on critical shear stresses computations is of paramount importance in the case of overloading.

Finally we point out that pavements thicker (15.0 cm and more of asphalt) than the one analyzed in this paper are more vulnerable to near-surface shear failure, especially when conventional bitumen is used.

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