Tensile Versus Compressive Moduli of Asphalt Concrete

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A laboratory investigation was performed to evaluate the modulus of asphalt concrete in compression and tension. Five modes of loading, namely, quasi-static compressive, quasi-static tensile, harmonic compressive, harmonic tensile, and alternate compressive tensile loads, were used at three temperatures of 5°C, 25°C, and 40°C (41°F, 77°F, and 104°F). At 5°C, the tensile and compressive moduli were very close but at higher temperatures, the compressive modulus was always higher. These results were used in the multilayer elastic program ELSYM5 to study the effect on the stress and strain distributions of varying the modulus of asphalt concrete. A simple bimodular analysis was used in which the compressive modulus was used for the top half of the asphalt layer and the tensile modulus for the bottom half of the layer. The multilayer analysis indicates that the incorporation of the tensile modulus in the analysis gives results different from those obtained using a single compressive modulus, resulting usually in the increased predicted fatigue and rutting lives. This suggests that the use of a bimodular method of analysis that can distinguish between compressive and tensile stresses and use the appropriate modulus accordingly is more rational and provides more realistic predictions of flexible pavement responses than single-modular methods.

Material characterization is an integral part of the pavement design and analysis process and should be related to the method of design or analysis used. Since pavement is a complex structure consisting of a number of materials with different properties, perfect mathematical description of the structure and a unique characterization of the material may not be possible. All characterization methods, therefore, use some simplifying assumptions to make the problem mathematically amenable.

Most structural response models based on layered theory do not consider the heterogeneity of the asphalt concrete material. They are mostly based on linear elastic or linear viscoelastic theory. In the linear elastic theory, the material in each layer is assumed to be homogeneous, isotropic, and linear elastic. Such material can be fully characterized by two elastic parameters such as the modulus and Poisson's ratio. The viscoelastic theory considers also the time rate of stresses and strains in the asphalt concrete layer, but the assumptions of homogeneity and isotropy are still considered valid. Since asphalt concrete consists of aggregates and an asphalt binder with two distinct properties, the assumptions of homogeneity and isotropy may not be valid. One way of considering such heterogeneity of asphalt concrete is to use two different modulus values for tension and compression rather than using a single modulus value.

The use of a single modulus value for asphalt concrete would be justified if the asphalt concrete layer under the action of the traffic loads underwent either tensile stress only or compressive stress only throughout the thickness of the layer. This would also be justified if the asphalt concrete had the same modulus values in both tension and compression. Neither of these cases is true. The asphalt concrete layer under the action of vehicular loads is partly in tension and partly in compression. Figure 1 shows the pattern of stresses and strains developed in the pavement system when a vehicle travels over a smooth pavement surface (*1*). The figure shows that the pavement layers are mostly subjected to compression, while tension is developed mostly at the bottom of stiff asphalt layers. Also, it was reported as early as the 1960s that the material behaves differently in tension and in compression (*2,3*). It is therefore more realistic to use different modulus values for asphalt concrete in tension and in compression in the analysis and design of pavements.

No standard method of material characterization is currently available to determine moduli and Poisson's ratios of asphalt concrete in both tension and compression. Also, the influence of using different modulus values for tension and compression on basic pavement design parameters is not known. More work is needed on this subject to evaluate these strength parameters for asphalt concrete under different loading and temperature conditions, which forms the basis of the present study.

OBJECTIVE

The objective of this study is to evaluate the modulus and Poisson's ratio of asphalt concrete under different loading and temperature conditions. Tensile and compressive parameters under static and dynamic conditions are determined in the laboratory. The effect on critical pavement design parameters of using such parameters is also determined.

NATURE OF ASPHALT CONCRETE RESPONSE

Asphalt concrete consists of aggregate particles coated with asphalt binder as illustrated in Figure 2. When the material is subjected to compression, compressive strength is developed because of the resistance to the shear stresses of both the aggregate interlock and the stiffness of the asphalt binder. For asphalt concrete in tension, the effect of the aggregate interlock is almost nonexistent, while the asphalt binder plays an important role in the tensile resistance of asphalt concrete. Therefore, it seems logical to expect asphalt concrete to have different behaviors in tension and in compression. Also, since the stiffness of the asphalt binder is largely affected by temperature and the aggregate stiffness is not, the difference between the tensile and compressive responses is expected to be different at different temperatures.

The task of material characterization is made complicated by the effect of rate dependency, environmental conditions, state of stress,

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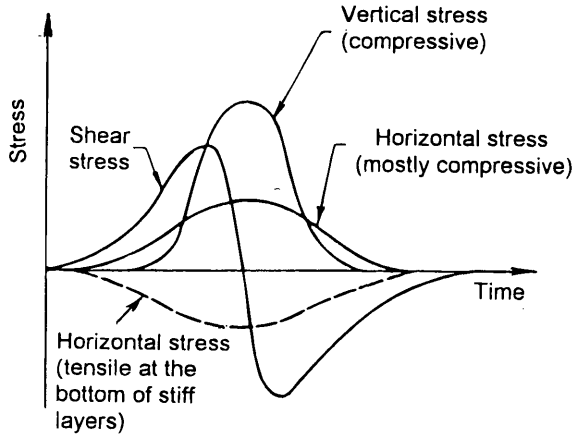


FIGURE 1 Pattern of stresses and strains developed in the pavement system under a wheel load moving on a smooth pavement surface.

and age on the properties and response of asphalt concrete. Thus, using simple assumptions in the characterization of the paving materials may not produce accurate results. Although not impossible, exact laboratory simulation of in situ conditions may be prohibitive both in time and in cost. Thus, all characterization techniques for paving materials are by necessity a compromise between rigor and practically. As such, laboratory test methods often use simplifications with the object of reproducing only those aspects of the in situ conditions that are likely to be most significant. Usually, the compromise is based on the average or limiting conditions that are believed to be critical with respect to pavement behavior.

Different modes of loading have been used by different researchers to characterize asphalt concrete in the laboratory, for example, direct tension, direct compression, and a combination of tension and compression such as the case of the diametral resilient modulus test. Also, both static and dynamic (harmonic and pulsating) loads have been used. The diametral resilient modulus test has been extensively used lately in many studies including the SHRP Long-Term Pavement Performance (LTPP) study. However, problems with the accuracy and reproducibility of such tests have been encountered.

The bimodular nature of asphalt concrete has been investigated by many researchers. Hargett and Johnson (*4*) found the compressive strength of asphalt concrete to be about 10 times the tensile strength. Kallas (*5*) conducted repeated load dynamic tests to investigate the dynamic modulus of the asphalt concrete in tension, tension-compression, and compression. He found that the dynamic modulus values under tension and tension-compression were as low as one-half of the dynamic compression modulus. Kennedy et al. (*6*) reported the permanent strain relationships for the triaxial tensile test and indirect tension test to be similar but both of them to be significantly different from those for the triaxial compression tests.

Von Quintas et al. (*7*) found the unconfined compression and indirect tensile resilient moduli not to be much different at low temperatures. However, the two modulus values were found to diverge greatly at higher temperatures. Bonaquist et al. (*8*) measured compressive and tensile moduli over a range of temperatures and frequencies and found greater dynamic compressive modulus values than indirect tensile modulus values. They also found the modulus-versus-temperature relationships to be different for different test procedures. Mamlouk (*9*) showed that the indirect tensile modulus was different than the moduli of compressive load types. He suggested refining the multilayer elastic analysis by using appropriate modulus values depending on whether the material is in tension or in compression. This seems rational because the asphalt concrete surface in pavement is partly in tension and partly in compression. If the tension and compression moduli differ significantly, then neither the compressive nor the tensile modulus alone would truly represent the asphalt concrete layer in the field.

LABORATORY TESTING AND RESULTS

In this study 35 hot-mix asphalt concrete cylindrical specimens were prepared, 102 mm (4 in.) in diameter and 203 mm (8 in.) in length. They were prepared using the California kneading compaction according to ASTM D3496. A dense aggregate gradation was used with a maximum size of 12.5 mm (1/2 in.) as shown in Table 1. An AC-40 asphalt cement was used with a content of 5.3 percent by weight of aggregate, which was the optimum asphalt content following the Marshall mix design procedure. The asphalt cement had the following properties:

1. Penetration: at 25°C, 100 g, 5 sec = 35;
2. Absolute viscosity = 3500 poise;
3. Kinematic viscosity = 350 cSt;
4. Ductility > 85 cm; and
5. Absolute viscosity after RTFO test = 8000 poise.

During compaction the number of blows was adjusted by trial and error to obtain the same bulk specific gravity as Marshall specimens. The average bulk specific gravity (saturated surface-

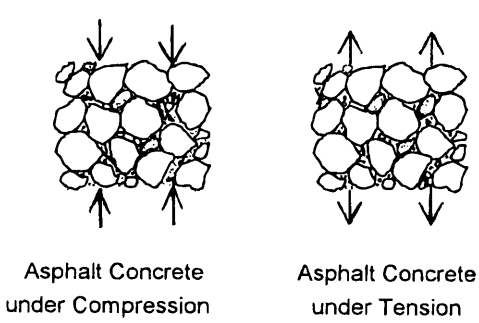


FIGURE 2 Asphalt concrete under compression and tension.

TABLE 1 Aggregate Gradation Used in Study

Sieve Size, mm (in.)	Percent Passing
12.5 (1/2)	100
9.5 (3/8)	85
4.75 (No. 4)	60
2.36 (No. 8)	49
1.18 (No. 16)	36
0.60 (No. 30)	24
0.30 (No. 50)	13
0.15 (No. 100)	7
0.075 (No. 200)	4

dry) of specimens was 2.319. Specimens were then grouped into five groups with the same average bulk specific gravity of each group.

Five laboratory tests were performed with the following loading conditions as illustrated in Figure 3:

1. Quasi-static axial compression with a rate of loading of 4.45 kN/sec (1,000 lb/sec). The maximum stress applied was approximately 275 kPa (40 psi).
2. Quasi-static axial tension with a rate of loading of 4.45 kN/sec (1,000 lb/sec). The maximum stress applied was approximately 275 kPa (40 psi).
3. Harmonic axial compression with a frequency of 3 Hz and a peak-to-peak stress of 275 kPa (40 psi) and a seating stress of about 35 kPa (5 psi).
4. Harmonic axial tension with a frequency of 3 Hz and a peak-to-peak stress of 275 kPa (40 psi) and a seating stress of about 35 kPa (5 psi).
5. Harmonic axial tension-compression with a frequency of 3 Hz and a peak-to-peak stress of 550 kPa (80 psi).

Seven different specimens were tested using each of these loading conditions, although not all the tests were successful due to minor problems with the machine and/or the measuring devices. Tests were performed at temperatures of 5°C, 25°C and 40°C (41°F, 77°F, and 104°F). Since the tests were nondestructive, each specimen was tested at the three test temperatures starting with the lowest temperature and ending with the highest temperature.

The arrangement of the linear variable differential transducers (LVDTs) attached to the test specimen inside the temperature-controlled chamber is shown in Figure 4. Two vertical spring-loaded LVDTs were attached to the specimen using clamps fixed to the specimen with epoxy. A 102-mm (4-in.) gauge length was used in the middle of the specimen height in order to reduce the "end effect." In addition, two horizontal spring-loaded LVDTs were attached to vertical posts and made contact with the specimen at two opposite sides at midheight. The bases of the specimen were fixed to the top and bottom loading heads of the machine with epoxy using the concrete capping device (ASTM C617). Since very small deformations were expected to be measured, proper specimen alignment and LVDT attachment were ensured. Also, care was taken to select the proper size and accuracy of LVDTs to ensure accurate measurements.

An electrohydraulic closed-loop machine equipped with an environmental chamber was used for testing. The machine was controlled by a microcomputer. Before testing, the LVDTs and the load cell were calibrated. During the test, the load and deformations were continuously recorded.

In case of quasi-static loading, the stress-strain relation was either linear or slightly nonlinear. The modulus was computed as the secant modulus of the stress-strain curve at 275 kPa (40 psi). The Poisson's ratio was computed as the negative of the ratio between the horizontal and vertical strains at 275 kPa (40 psi). In case of either compressive or tensile harmonic loading, the dynamic modulus was computed by dividing the stress amplitude by the strain

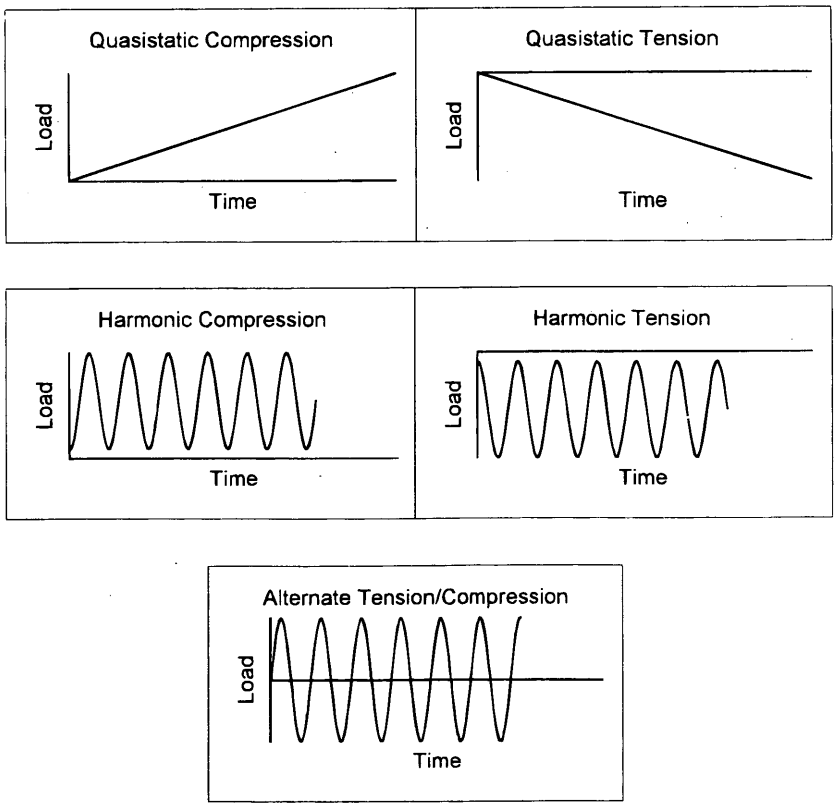


FIGURE 3 Load patterns used in the laboratory testing.

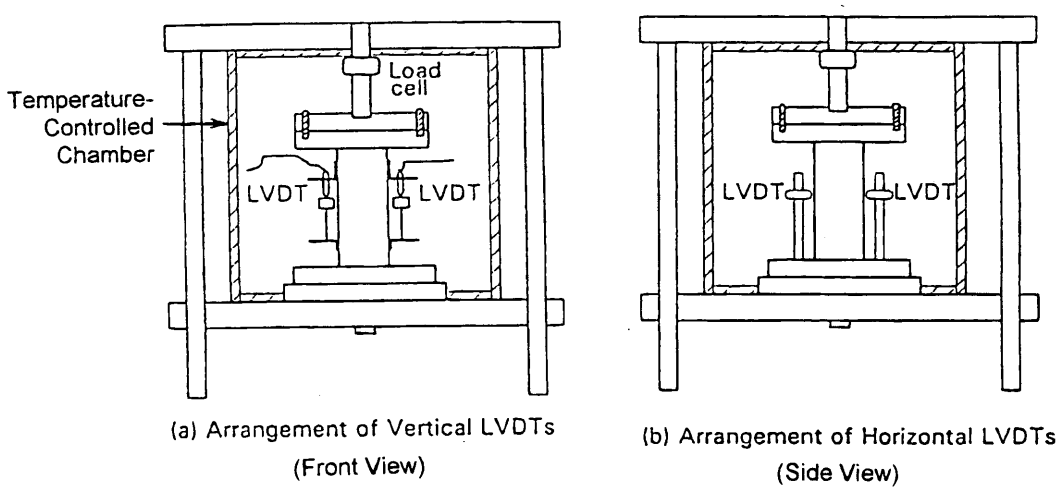


FIGURE 4 Schematic diagram of specimen and LVDT setup.

amplitude (ASTM D3497). For the alternate tension and compression test, separate tensile and compressive moduli were determined by dividing the stress amplitude by the strain amplitude in each case. The Poisson's ratio was computed as the negative of the ratio between the horizontal and vertical strain amplitudes. Table 2 shows the average modulus values for different loading conditions and test temperatures. The table shows that the modulus values are within the typical range of values obtained by other researchers. However, Poisson's ratio results were not reliable. Most Poisson's ratios were quite low and inconsistent. This problem has been reported in several studies.

TABLE 2 Average Modulus Values at Different Loading Conditions and Test Temperatures

Test Type		5°C	25°C	40°C
Quasi-Static Compression		14704	4258	676
Quasi-Static Tension		10681	3632	266
Harmonic Compression		13558	6156	1741
Harmonic Tension		14534	4250	619
Alternate	Compression	14202	6896	1378
	Tension	16457	6259	910

ANALYSIS OF LABORATORY RESULTS

Figure 5 shows a plot of mean modulus values given in Table 2. It can be seen from Figure 5 that increasing the temperature decreases the modulus for all modes of loading. Comparing the tensile and compressive moduli at each temperature shows that at 5°C (41°F), the mean tensile modulus values were slightly higher than the cor-

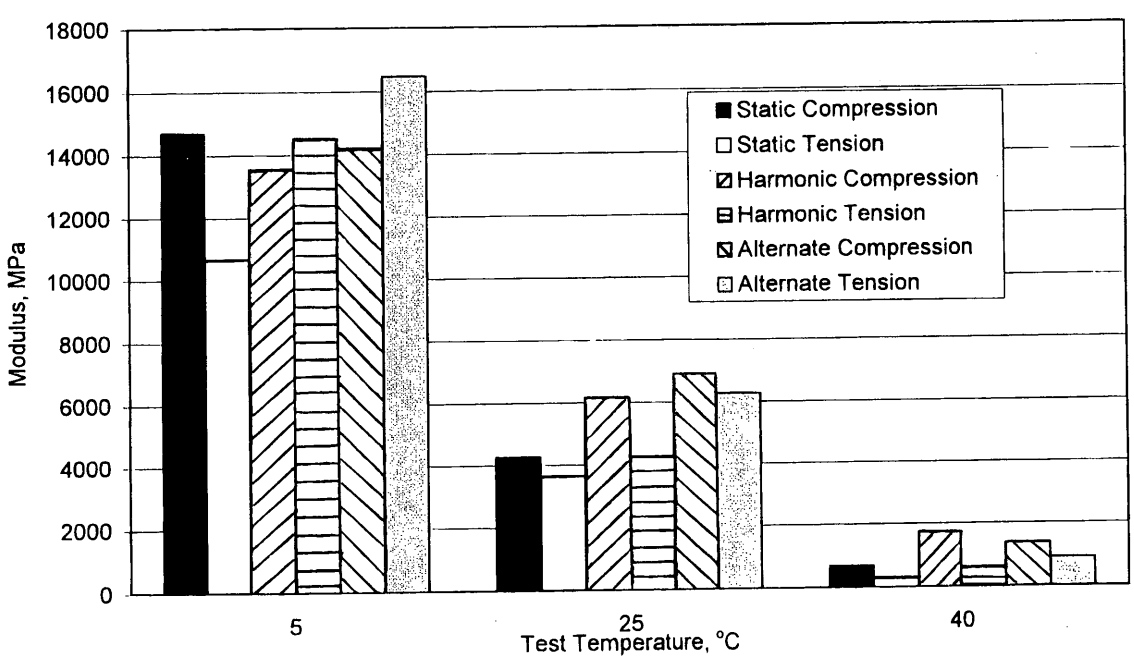


FIGURE 5 Modulus values at different test temperatures.

responding compressive values except in the quasi-static case. In general, the tension and compression modulus values were close to each other and did not follow any specific trend. At low temperatures, the asphalt binder has a high stiffness, which contributes significantly to the stiffness, and hence the modulus, of the asphalt aggregate mixture. Thus, at low temperatures, asphalt concrete seems to behave similarly in tension and in compression.

At 25°C (77°F), the mean compressive modulus values were higher than the corresponding tensile modulus values for all loading conditions. The maximum difference between the two moduli was in the harmonic tensile and compressive loading case in which the average compressive modulus was about 1.5 times the average tensile modulus. The smallest difference was in the alternate tension-compression loading case in which the compressive modulus was only about 10 percent higher than the corresponding tensile modulus.

At 40°C (104°F), however, there was a great difference between the tensile and compressive modulus values. The compression modulus was about three times as high as the tension modulus in both the static and harmonic loading cases, whereas it was about 50 percent higher in the alternate tension-compression loading mode.

The reason for obtaining tensile modulus values lower than the corresponding compressive values at high temperatures can be explained by the fact that the tensile stiffness of the mixture is contributed mostly by the tensile resistance of the asphalt binder, whereas aggregate particles contribute very little. Since the stiffness of the asphalt binder is largely reduced at high temperatures, the tensile modulus of the asphalt concrete is also reduced. On the other hand, most of the load is carried by the aggregate particles when the mixture is subjected to compression, whereas the asphalt binder has little contribution. Hence, at high temperatures the compressive modulus is not largely reduced when compared to the tensile modulus.

This clearly indicates that asphalt concrete does not behave similarly in tension and in compression, especially at high temperatures. Although it may be logical to consider similar tensile and compressive moduli at low temperatures, the assumption of similar moduli at higher temperatures is not valid. This is also demonstrated by the analysis of variance (ANOVA) statistical tests that were conducted to evaluate the significance of loading conditions and test temperatures on the modulus values. A level of significance of 5 percent was used in this study. The ANOVA results indicate that both test temperature and loading condition are significant. As expected, the most significant factor was the test temperature.

ANALYSIS OF FIELD CONDITIONS

The ELSYM5 multilayer elastic computer program (*10*) was used to evaluate the stress distribution within the asphalt layer under typical field conditions. Critical parameters such as the tensile strain at the bottom of the asphalt layer and the compressive strain at the top of subgrade were also computed. Three typical flexible pavement sections were considered and designated thin, medium thickness, and thick with layer thickness as shown in Table 3. The subgrade was assumed to have a semiinfinite thickness. The laboratory obtained tensile and compressive moduli of asphalt concrete at the three temperatures of 5°C, 25°C, and 40°C obtained by harmonic loadings were used in the analysis. The moduli of base, subbase, and subgrade materials were assumed to be 550, 275, and 140 MPa (80, 40, and 20 ksi), respectively. Poisson's ratios for asphalt concrete were assumed to be 0.30, 0.35, and 0.40 at 5, 25, and 40°C, respectively. Poisson's ratios measured during the laboratory testing were not used because they were unreliable. Poisson's ratios for base, subbase, and subgrade were assumed to be 0.35, 0.35, and 0.45, respectively. A circular uniformly distributed load with a 40-kN (9-kip) magnitude and a 690-kPa (100-psi) intensity was used.

TABLE 3 Layer Thicknesses of Analyzed Pavement Sections

Layer Type	Layer Thickness, mm (in.)		
	Thin	Medium	Thick
Asphalt Concrete	51 (2)	152 (6)	254 (10)
Base	102 (4)	152 (6)	203 (8)
Subbase	102 (4)	203 (8)	305 (12)

Two methods of analysis were used for all three pavement sections. In the first method, only the compressive modulus of asphalt concrete was used for the whole thickness of the asphalt concrete layer. In the second method, the asphalt concrete layer was divided into two halves, with the top half assigned the compressive modulus and the bottom half the tensile modulus. Figure 6 shows the distribution of vertical and radial stresses in the thin pavement at three temperatures for the two methods of analysis. Similarly, Figures 7 and 8 show the corresponding results for the medium thickness and thick pavements, respectively. In all three figures, it can be seen that both radial and vertical pressure distributions at 5°C (41°F) are essentially identical for both methods of analysis.

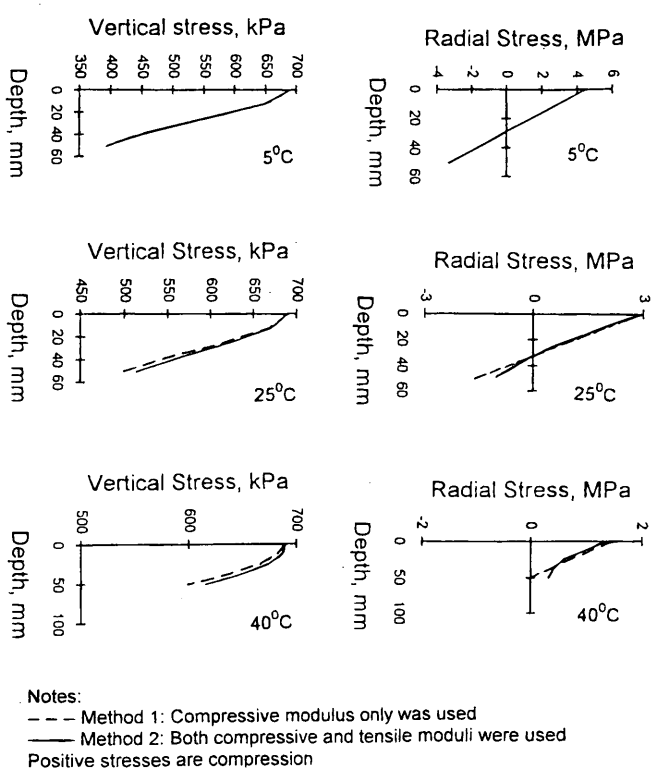
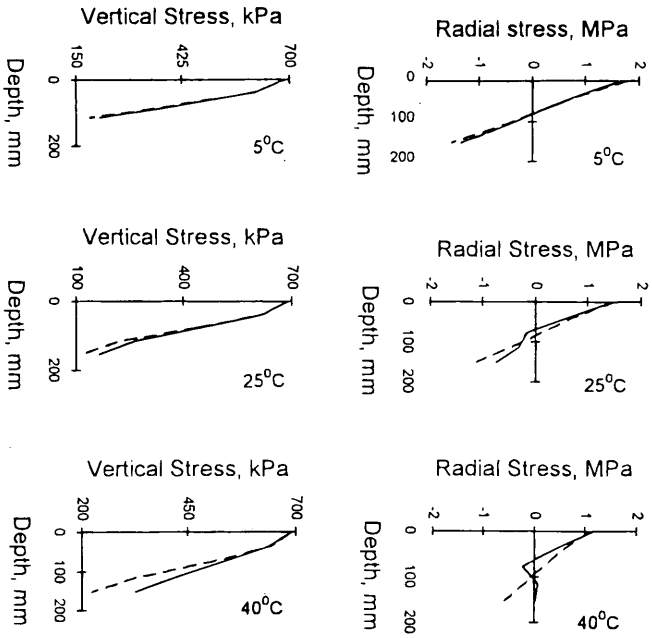


FIGURE 6 Stress distributions in thin pavements. (- - -)Method 1: compressive modulus only was used. (—)Method 2: both compressive and tensile moduli were used. Positive stresses are compression.



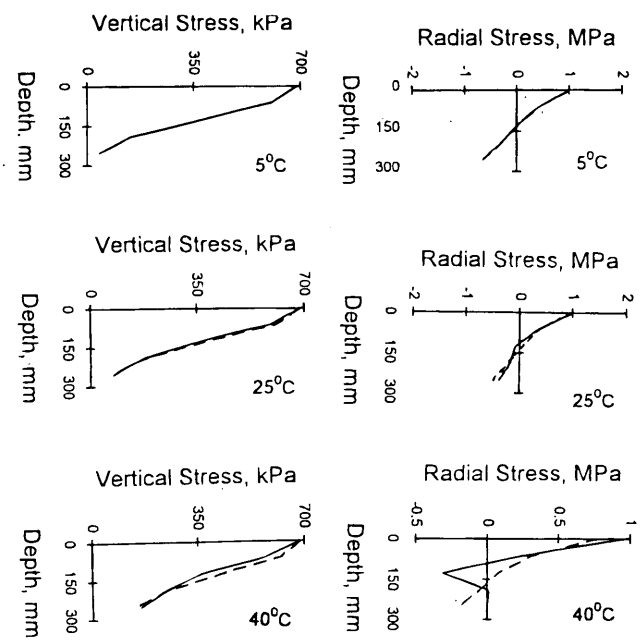
Notes:
– – – Method 1: Compressive modulus only was used
—— Method 2: Both compressive and tensile moduli were used
Positive stresses are compression

FIGURE 7 Stress distributions in medium-thickness pavements. (- - -)Method 1: compressive modulus only was used. (—)Method 2: both compressive and tensile moduli were used. Positive stresses are compression.

For the thin pavement (Figure 6) at 25°C (77°F), the tensile radial stress at the bottom of the asphalt layer was reduced by about 45 percent when the bimodular method of analysis was used. The vertical pressure distribution, however, did not change much throughout the asphalt layer. At 40°C (104°F) the compressive modulus method produced a small tensile radial stress at the bottom of the asphalt layer, whereas the use of the bimodular analysis produced a compressive radial stress. At 25°C the use of the bimodular analysis increased the tensile strain at the bottom of the asphalt layer by about 7 percent whereas at 40°C it was reduced by 40 percent. For all temperatures, there was no significant difference in the vertical deformation at the top of the subgrade.

For the medium-thickness pavement (Figure 7) at 25°C, the tensile radial stress at the bottom of the asphalt layer was reduced by about 30 percent when the bimodular analysis was used as compared with the case of using the compressive modulus only. The vertical stresses throughout the layer, however, remained practically unchanged. At 40°C the compression-only analysis gave a tensile radial stress at the bottom of the asphalt concrete layer but the tension-compression moduli combination gave a compressive radial stress. At all temperatures, the use of bimodular analysis caused a reduction in the tensile radial strain at the bottom of the asphalt layer as well as the vertical deformation on top of the subgrade. The reduction ranged from 5 to 35 percent.

For the thick pavement (Figure 8) at 25°C, the tensile radial stress at the bottom of the asphalt concrete layer was reduced by about 28 percent when the bimodular method of analysis was used as compared with the case of using the compressive modulus value only. At 40°C the combination of tension and compression moduli gave a very small compressive radial stress at the bottom of the asphalt



Notes:
– – – Method 1: Compressive modulus only was used
—— Method 2: Both compressive and tensile moduli were used
Positive stresses are compression

FIGURE 8 Stress distributions in thick pavements. (---)Method 1: compressive modulus only was used. (—)Method 2: both compressive and tensile moduli were used. Positive stresses are compression.

layer but induced a tensile radial stress in the middepth of the asphalt layer. This was also observed in the medium-thickness pavement section. The use of the bimodular analysis caused a slight increase (varying from 5 to 10 percent) in the radial tensile strain at the bottom of the asphalt layer as well as the displacement on top of the subgrade.

CONCLUSIONS

Based on the observations obtained from the laboratory measurements and the multilayer elastic analysis, the following conclusions can be drawn:

1. Asphalt concrete resists tensile and compressive stresses differently because of the different contributions of asphalt and aggregates to the tensile and compressive stiffnesses. Also, since the stiffness of the asphalt binder is largely affected by temperature whereas the aggregate stiffness is not affected, the difference between the tensile and compressive moduli is typically different at different temperatures.
2. Asphalt concrete has similar moduli in tension and compression at low temperatures, but those moduli are different at high temperatures. The difference between the tensile and compressive moduli becomes more significant when the temperature increases.
3. At high temperatures the tensile modulus is always lower than the compressive modulus, with the tensile modulus in some cases as low as one-third of the compressive value.
4. Since the asphalt concrete layer undergoes both tensile and compressive stresses while the tensile and compressive moduli are typically different, more accurate results can be obtained when the appropriate modulus is used in multilayer elastic analyses.
5. When both compressive and tensile moduli were used in the top and bottom halves of the asphalt concrete layer, respectively, there was no significant change in the vertical compressive stresses in most cases but the radial tensile stress at the bottom of the layer was lower than that obtained by using the compressive modulus only. The reduction was about 45 percent in the case of thin pavements and up to about 28 percent in the case of thick pavements.
6. The use of the bimodular analysis causes a reduction in the tensile strain at the bottom of the AC layer as well as the vertical compressive strain on top of the subgrade of medium thickness pavements at all three temperatures. This means it increases the predicted fatigue life as well as the rutting life of the pavement structure.
7. Further research could provide a pavement analysis method that would be able to distinguish between compressive and tensile locations within the asphalt concrete layer and use the appropriate modulus at different locations. An iterative procedure could be used for this purpose.

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