Comparison of Fundamental and Engineering Properties of Asphalt Concrete Mixtures Subjected to Compressive and Tensile Loadings

B. S. Underwood
Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, NC, USA

T.Y. Yun
Dept. of Highway Division, Korea Institute of Construction Technology, Goyang-Si, Gyeonggi-Do, Republic of Korea

Y. R. Kim
Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, NC, USA

ABSTRACT: It is well known that hot mix asphalt concrete (HMAC) shows different engineering behavior under compressive and tensile loading. Conventional thinking suggests that under compression aggregate particles move and interlock thus stiffening and strengthening the material. This view focuses mostly on the response at high temperatures, but yields little insight into the behavior at lower temperatures. In tension, damage in the form of micro- and macro-cracks perpendicular to the loading direction is thought to be the primary mechanism that drives performance. This view focuses on the region where the material is relatively stiff and does not consider the response at temperatures where the binder easily deforms. In this paper, the properties of HMAC subjected to compressive and tensile loading are examined over the broad range of conditions that the material may be subjected to in service. Comparisons of the linear viscoelastic (LVE) characteristics of HMAC for the different loading modes are made using temperature/frequency test results and it is found that the LVE properties under tensile and compressive loading are the same. The material responses under higher loading levels are studied by examining various engineering parameters. Comparisons of strength, strain tolerance and anisotropy are made using the measured responses from constant rate tests at a range of temperatures and strain rates. Differences in the engineering behaviors are found, discussed and quantified where appropriate.

KEY WORDS: asphalt concrete, linear viscoelastic, anisotropy, strength, strain tolerance, viscoelastic continuum damage model

1 INTRODUCTION

In service, hot mix asphalt concrete (HMAC) is subjected to a broad range of environmental and loading conditions in various combinations. These conditions ultimately influence the response and performance of pavements constructed with HMAC. For all of the potentially infinite conditions which exist, there are certain ones that are known to be critical. For example, the HMAC response to high load levels at elevated temperatures is critical to the rutting performance because this is when the rate of permanent deformation accumulation is greatest. Similarly, the response to high load repetitions at intermediate to low temperatures is critical to the fatigue cracking (both bottom-up and top-down) performance. The modeling and analysis of these conditions is complicated by the fact that the composite nature of HMAC may result in drastically different behaviors under tensile and compressive loading.

While the critical state concept is useful in simplifying many design and analysis protocols it leads to incomplete information on the fundamental behavior of many materials. Such information is important as the industry attempts to move towards more mechanistically based procedures. In these procedures, the critical state may not be explicitly considered and as a result the behavior at all states becomes important to the final answer (whether the final answer is pavement thickness, rut depth, etc.). It is important to stress that the behavior at these non-critical states may be important to the overall performance, but the current state of knowledge does not allow for the assessment of this importance.

Many studies have focused on either the tensile or the compressive characteristics of HMAC. Since the compression behavior is linked to permanent deformation, most studies of the compression behavior are based on experiments at high temperatures and high load levels (c.f. Kaloush 2001). For a similar reason, most studies focusing on fatigue perform tension-based experiments (direction tension, indirect tension, beam fatigue, etc.) at intermediate to low temperatures and with a high number of repetitions (c.f. Rao Tangella et al. 1990). When the same materials are tested in the compression and tension modes many times they are not conducted under the same temperature and loading conditions (Grenfell et al. 2008). The objective of this paper is report on a series of experimental and analytical studies performed on a single, standard HMAC material tested in similar ways in tension and compression directions. Comparisons are made in the low strain region where the material responds linear viscoelastically and at higher strains where damage and/or aggregate reorientation may influence the material response. It is believed, although it cannot be proven, that the major themes and trends observed with this single mixture are representative of what would be observed with similar experiments in other asphalt concrete materials. This is believed to be particularly true for the material behaviors in the linear-viscoelastic range. However, the relative magnitudes and significance of some of the observations are expected to vary with changes in certain key mixture variables, such as with the use of highly gap graded gradations, stone matrix asphalt concrete, use of rounded aggregate, etc.

2 MATERIALS AND SPECIMEN FABRICATION

The mixture used for this study was the Control mixture for the Federal Highway Administration’s Accelerated Load Facility tests. It contains a nominal maximum size of aggregate of 12.5 mm and the gradation is of the coarse type. The asphalt binder is graded at PG 70-22 and constitutes 5.3% of the total mix mass.

All specimens were mixed in the laboratory, prepared for testing using standard procedures (Kim et al. 2005, Kim et al. 2008). All test specimens were compacted in the Superpave Gyratory compactor to a height of 178mm and a diameter of 150mm. Test specimens were cored and cut from these gyratory specimens to obtain as uniform a material as possible. All tests were conducted at air void contents of 4±0.5%.

Anisotropy specimens, both tension and compression, were 75mm in diameter and 90mm in height. This geometry was chosen so that specimens could be obtained oriented either horizontally, or vertically with regards to the gyratory compaction direction. Samples cored in the direction of compaction are referred to as *vertical* samples whereas samples cored perpendicular to this direction are referred to as *horizontal* samples. A numerical study using finite element analysis showed that for the chosen geometry that the inconsistent end-conditions between the tension and compression tests was too significant to directly compare the two results. It was also concluded that this issue should not affect the study of results within each particular test method.

3 EXPERIMENTAL METHODS

Two basic test methods have been employed in this study; 1) temperature and frequency sweep oscillation experiments (dynamic modulus tests) and 2) constant actuator displacement rate experiments (monotonic tests). These tests are used to assess the low-strain and high strain characteristics respectively. A brief description of these experiments is given below, and a more thorough description has been given in other sources (Kim et al. 2005, Kim et. al 2008). In each test the on-specimen axial and radial deformations were measured using LVDTs centered at the specimen mid-height. Load and deformation were recorded throughout each test and stored for further analysis. All experiments were performed using a 100 kN MTS closed loop servo-hydraulic load frame.

3.1 Dynamic Modulus Tests

The dynamic modulus, $|E^*|$, was measured using frequency sweep tests (25, 10, 5, 1, 0.5, 0.1, 0.05 and 0.01 Hz) at four different and fixed temperatures (-10, 10, 35 and 54°C). Tests were conducted in either compression only mode (zero-maximum stress) or tension-compression mode (zero-mean stress). The test was performed with the test machine in load control and the applied load was adjusted through trial and error to yield an on-specimen strain magnitude of 50 – 75 *me*. The $|E^*|$ was computed using the method presented in AASHTO TP 62-07 (2007). At least three replicate tests are performed to obtain the representative $|E^*|$ value.

3.2 Monotonic Tests

The tensile and compressive strengths and strain responses were determined using constant machine actuator rate experiments. Tests are performed at a range of temperatures and strain rates to yield behaviors ranging from mostly viscoelastic and damage to mostly viscoplastic. Monotonic tests are conducted over a range of temperatures and rates: for compression tests the temperatures and rates ranged from 8.7×10^{-4} ε/s at 55°C to 2.5×10^{-5} ε/s at 5°C; for tension tests the temperatures and rates ranged from 3.3×10^{-4} ε/s at 40°C to 2.5×10^{-5} ε/s at 5°C. Only a single test is performed at each rate and temperature combination.

3.3 Anisotropy Tests

A limited number of tests are performed to examine the effect of anisotropy on both the LVE and damage characteristics of HMAC. The experiments themselves are identical to those described above except for the aforementioned differences in specimen size. Constant rate tests were performed at 5°, 25°, and 40°C and target strain rates of 1.0×10^{-5} ε/s, 5.0×10^{-4} ε/s, and 3.3×10^{-3} ε/s respectively. Two replicates are tested at each of the rate and temperature combinations and the average of these was used for the analysis

4 RESULTS AND DISCUSSION

4.1 Dynamic Modulus

The $|E^*|$ is an important material characteristic because it represents the fundamental LVE stiffness response of HMAC. As such it is often used in pavement response models to determine the stress and strain response of an HMAC pavement subjected to some loading condition. Literature on this topic is conflicted, some researchers suggest that the |*E**| is dependent upon the loading direction, tension-compression versus compression (Advanced Asphalt Technologies 2004, Gibson 2006) while others have reported statistically similar results for indirect tension, compression, impact resonance and others (Kim et al. 2004, Kweon and Kim 2006, Lacroix and Kim 2008). Unfortunately, much of the work suggesting that the |*E**| is directionally dependent has not been reported on in sufficient enough detail to fully judge the reported conclusions. It can be noted though that extreme care should be taken when determining if a given loading yields a different |*E**| because the effects of hardening, damage, and/or other mechanisms may confound the analysis. It is of critical importance that this judgment is based on experimental data that is free from such confounding factors. For this reason all |*E**| tests in this study were performed with strain amplitudes of approximately 50 – 75 με. In addition, the total accumulated strain in all of the zero maximum stress tests was less than 1500 με.

There is some theoretical justification for the existence of different apparent |*E**| calculated from tension-compression and compression only modes (Tschoegl 1989). However, the difference would be small, perhaps even smaller than normal experimental error; as long as the calculations are performed on cycles occurring after the steady state condition is reached, which in some cases can occur in as few as 5-10 cycles. For the experiments conducted in this study more than 20 cycles are applied for every temperature and frequency combination, thus it is believed that this theoretical difference should be small.

The results for both zero-maximum and zero-mean |*E**| tests are shown in the form of |*E**| mastercurves in Figure 1 in both log-log and semi-log scales. Details of constructing these curves are given elsewhere (Kim et al. 2005), but in short they graphically demonstrate the LVE behavior over the wide range of temperatures and frequencies that could be expected to occur in service. Reduced frequency can be interpreted in terms of physical frequency; as frequency increases reduced frequency increases, or in terms of temperature; as temperature increases reduced frequency decreases. A second function, the time-temperature shift factor function can be used to convert between temperature, frequency and reduced frequency. Although this function is not shown here, due to space limitations the function is found to be almost identical between the two test protocols and one may interpret a given reduced frequency as the same temperature and frequency combination for either of the two protocols.

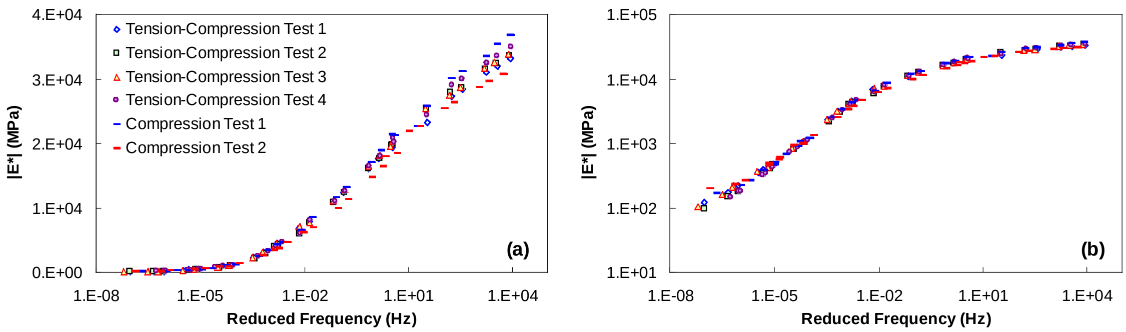

Figure 1**: Effect of loading type on measured dynamic modulus in; (a) semi-log and (b) log-log space.**

In Figure 1, replicate data are included to provide a sense of the statistical significance of the observations. Overall, the comparisons are very favorable, and little difference is seen between the zero-mean and zero-maximum stress tests. The compression protocol does yield a slightly higher modulus at 54°C and 0.1 Hz, however, this is the last data point and was subject to the highest amount of permanent strain accumulation. In light of this fact and due to the agreement at other temperatures and frequencies it is concluded that at least for small strains (50 – 75 με), asphalt concrete does not display different behavior under tensile or compressive loading. This conclusion is of course highly dependent on the fact that neither damage nor plasticity induced hardening were significant in these experiments.

4.2 Monotonic

Monotonic tests are performed to determine how the compressive and tensile behaviors differ when damage and hardening mechanisms occur. This particular test method is chosen because; 1) it can be performed relatively quickly, 2) it produces a uniform state of stress in the body, 3) it can be performed reliably over a wide range of temperatures and rates, 4) it can be performed equally well in tension and compression modes (with the available test equipment), and 5) the data can be analyzed to yield an advanced material model for describing the damage characteristics of HMAC. Typical results of tension and compression monotonic tests at very similar test rates are shown in Figure 2. It can be seen from this figure that both tension and compression results show a reduction in strength with increasing temperatures. It can also be seen that the compression test shows substantially higher strength and strain tolerance than does the tension test.

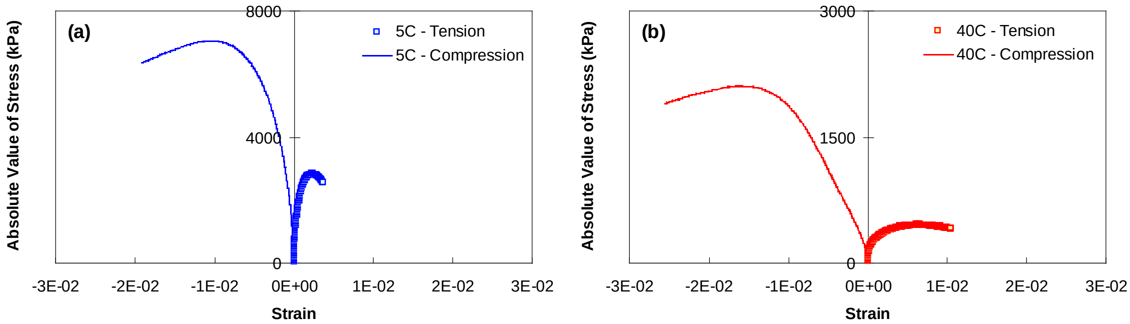

Figure 2**: Typical stress strain behavior for tension and compression monotonic tests.**

Complications arise in the interpretation of monotonic tests because machine compliance issues are present and these issues differ according to the test condition. As a result of this complication, and because the time-temperature superposition principle used to construct LVE mastercurves has been proven valid for high damage levels in both tension and compression (Kim et al. 2008); data interpretation is made using mastercurves for various engineering parameters. The results of this analysis are shown in Figure 3 for strength, strain tolerance, and dilation (volumetric strain). In these figures the x-axis is reduced strain rate and can be interpreted in a way similar to reduced frequency. As the physical rate increases or the temperature decreases the reduced rate increases. The axial strain and strength curves are absolute values for visual simplicity. Also shown in this figure is the best fit curve for each loading direction as well as the ratio of the given parameter from compression tests to the parameter from tension tests. The ratio is computed at a fixed reduced strain rate.

The first observation that is clear from Figure 3(a) is that the compressive strength of HMAC is substantially higher than the tensile strength for all temperatures and rates tested. The difference between the strength is proportionally greatest at the low reduced rates and this is believed to be a result of the higher influence of aggregate movement and interlock. These results may also be due in part to the fact that compressive stress does not directly cause microcracks. Instead, microcracks which do occur must be induced through local tensile strain irregularities or through global Poisson's effect, and tend to orient themselves parallel to the loading direction. As such the net effect of a given volume of microcracks on the global behavior in compression is less than an equivalent volume under tensile loading. It should be noted that the existence of microcracks in the compression tests has not been confirmed with the same rigor that has been given for tensile loading (Kim et al. 1988). However, it is felt that such cracking does exist and is important to HMAC behavior in compression because the tests in this study showed vertical macrocracks at the conclusion of the experiment. It is hypothesized that these vertical macrocracks evolved from microcracks throughout the test.

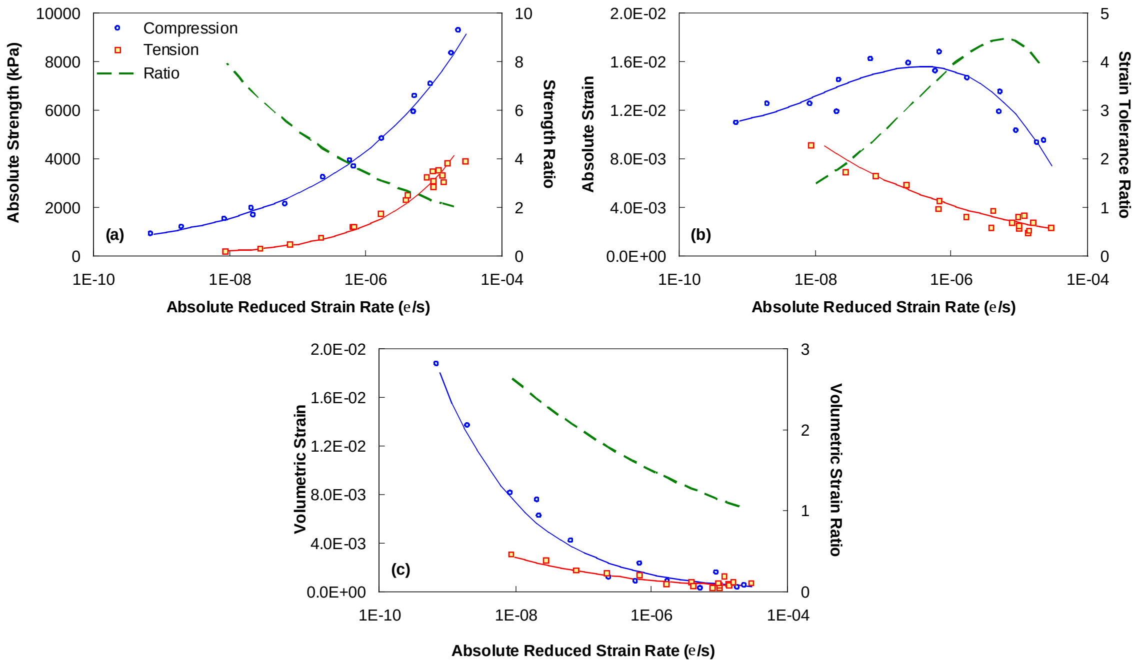

Figure 3**: Effect of monotonic loading type on engineering parameters; (a) absolute value of strength, (b) absolute value of axial strain, and (c) volumetric strain.**

It is also observed from Figure 3(b) that the compression tests are more tolerant of axial strain than the tension tests. In the case of tension tests the material shows a consistent increase in strain tolerance as the reduced strain rate decreases. This behavior is expected based on historical experience with ductility tests on asphalt binder at different test temperatures, but it is unclear whether this behavior extends to extremely low reduced rates or if an elastic-plastic-like plateau value is reached at some point. Compression tests on the other hand show more complicated behavior. At extremely high reduced rates the compression tests show an increase in failure strain with reducing rate. The rate of this increasing strain tolerance is much higher than with tension tests indicating an increased sensitivity to strain rate for compression testing. However, at reduced strain rates below approximately $1\text{x}10^{-6}$ ε/s the tests begin to show a reduced strain tolerance with slower loading rates. The point of slope change may represent a transition in dominant mechanisms from microcrack related to dilation and permanent deformation related. This hypothesis is supported by the volumetric strain behavior which begins to show a rapid increase at around $1\text{x}10^{-6}$ ε/s.

4.3 Anisotropy

Anisotropy in asphalt concrete can occur due to two different conditions; that which is inherently present due to preferential aggregate orientation and that which is induced through deformation. Inherent anisotropy is strongly influenced by the compaction method and in this study the gyratory compaction method, which tends to cause aggregates to orient themselves randomly in the horizontal plane but with their long axis flat in the vertical plane, was used. Additional anisotropic mechanisms may also be induced as specimens deform and aggregates begin to move or when microcracks begin to occur. In this paper the influence of both induced and inherent anisotropy has been examined as a function of loading direction. The effects have been examined at low strain and high strain ranges. Due to discrepancies between field and gyratory compaction techniques, it is possible that observations made from these experiments do not directly translate to field conditions. However, the authors believe that the mechanisms involved in the anisotropic behavior are similar. The goal of this study is to establish a proper understanding of the anisotropic behavior of the asphalt concrete in a highly controlled environment, which will eventually lead to better understanding of field behavior.

4.3.1 Anisotropy Dynamic Modulus Tests

The results of dynamic modulus tests in zero-mean and zero-maximum modes on both horizontal and vertical cores are shown in Figure 4. As can be seen from this figure, no clear difference in |*E**| exists between the horizontal and vertical cores at most frequencies. For the small strains used in |*E**| tests aggregate mobilization should be minimal, if there is any, and the inherent anisotropy caused by preferential aggregate orientation does not seem to affect the |*E**| values in any important way. This finding is important because it means that |*E**| tests performed on a plane parallel to the axis of symmetry will yield the same |*E**| values as tests on planes perpendicular to the axis of symmetry. Experimental verification of this finding can also be found in the work of other researchers (Kim et al. 2004, Lacroix and Kim 2008).

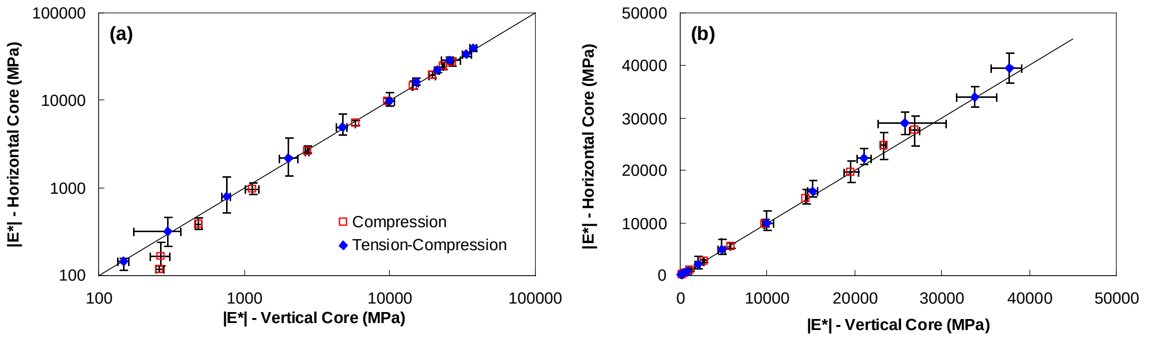

Figure 4**: Comparison of |E*| between horizontal and vertical cores in; (a) logarithmic and (b) arithmetic scales.**

In Figure 4(a) it is observed that at the lowest moduli values the vertically cored, zero-maximum stress specimens have slightly higher |*E**| values than the equivalent horizontally cored specimens. It is believed that for these points the linear range has been exceeded because of the accumulated strain caused by the end plate and seating load. By contrast, tension-compression tests, which use a seating load of zero, and show very little accumulated strain show no such divergence.

4.3.2 Anisotropy in Tension

The results of anisotropy monotonic tension tests are presented in Figure 5, in terms of different engineering properties. It is seen from this figure that there is little difference in strength, strain tolerance, or initial modulus values between horizontal and vertical cores for all temperatures and strain values tested. The initial modulus values are obtained by best fitting the stress-strain behavior up to a strain level of 75 με. It is not rigorously valid in a LVE sense, but does give an indication of the LVE material response and does support the findings from the |*E**| testing, where it was seen that horizontal cores and vertical cores yield the same |*E**| values. Note that the error bars shown in Figure 5, and subsequent similar figures, represent the range in values obtained from replicate tests. Based on the results shown in this figure it is concluded that anisotropy due to aggregate orientation does not have a significant impact on the tensile behavior of HMAC. It is also concluded that damage induced anisotropy in tension is not significantly affected by the aggregate orientation.

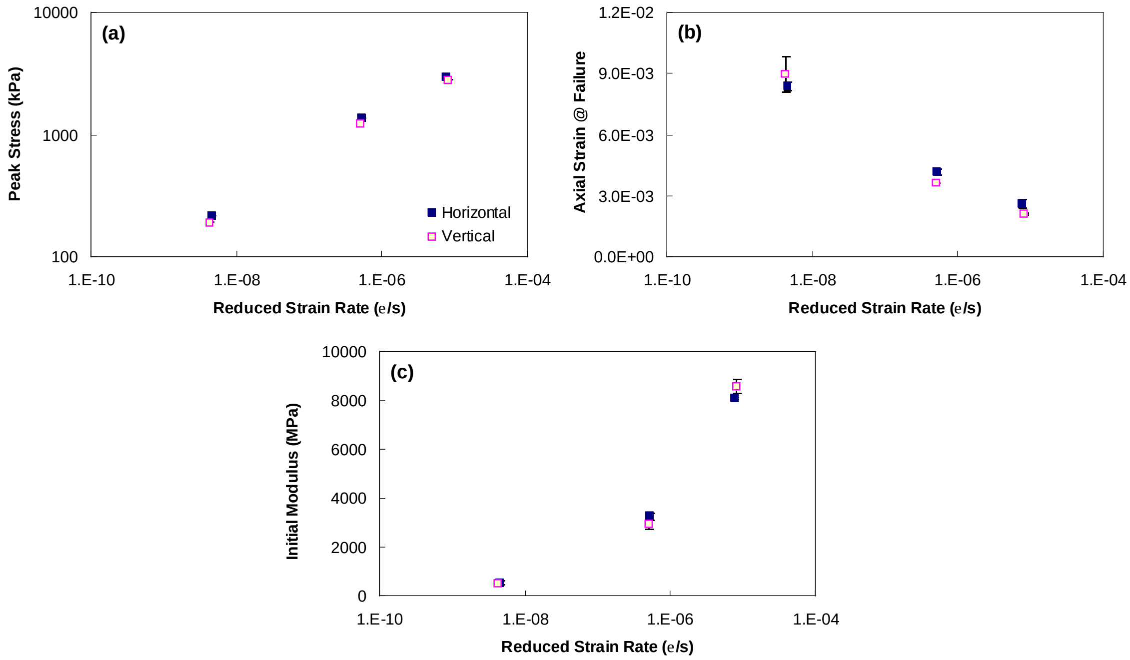

Figure 5**: Effect of anisotropy in uniaxial tension on; (a) strength, (b) axial strain at failure, and (c) initial modulus.**

4.3.3 Anisotropy in Compression

The results of anisotropic monotonic compression tests are presented in Figure 6. The same parameters examined for the tension tests are also examined for these tests. It is seen that under compressive loading the role of anisotropy, particularly with regards to strength, Figure 6(a), is much greater than its impact with tensile loading. The increased strength in vertical specimens is attributed to the aggregate interlocking effect. In the vertical tests, the aggregates are preferentially oriented with their long axis perpendicular to the loading direction, whereas in the horizontal tests the aggregates are preferentially oriented with their long axis parallel to the loading direction. The better interlocking in the vertical direction results in greater resistance to compressive deformation in that direction. Since the degree and amount of aggregate reorientation is directly proportional to the stiffness of the continuum, this effect should be reduced at the fastest reduced rates and the experimental data show that at the fastest rates that the strength of the vertical and horizontal cores are similar. Although the aggregate reorientation effect should be reduced at the fast reduced frequencies, the effect of induced anisotropy due to microcracking should be amplified. In this case it appears that the preferential orientation of aggregate does not substantially affect how damage induced anisotropy reduces the strength. This effect may be present in the strain tolerance since from Figure 6(b), the highest reduced rate shows a large discrepancy. However, only a single test was performed for the fasted reduced rate in both the horizontal and vertical directions and the replicate data at the slowest reduced rate suggests a great deal of variability so the reliability of this conclusion is questionable. Finally, it is also seen that there is no effect of aggregate orientation on the initial modulus. Again, this finding supports the results from the compression-only $|E^*|$ tests where no difference in horizontal and vertical cores was observed.

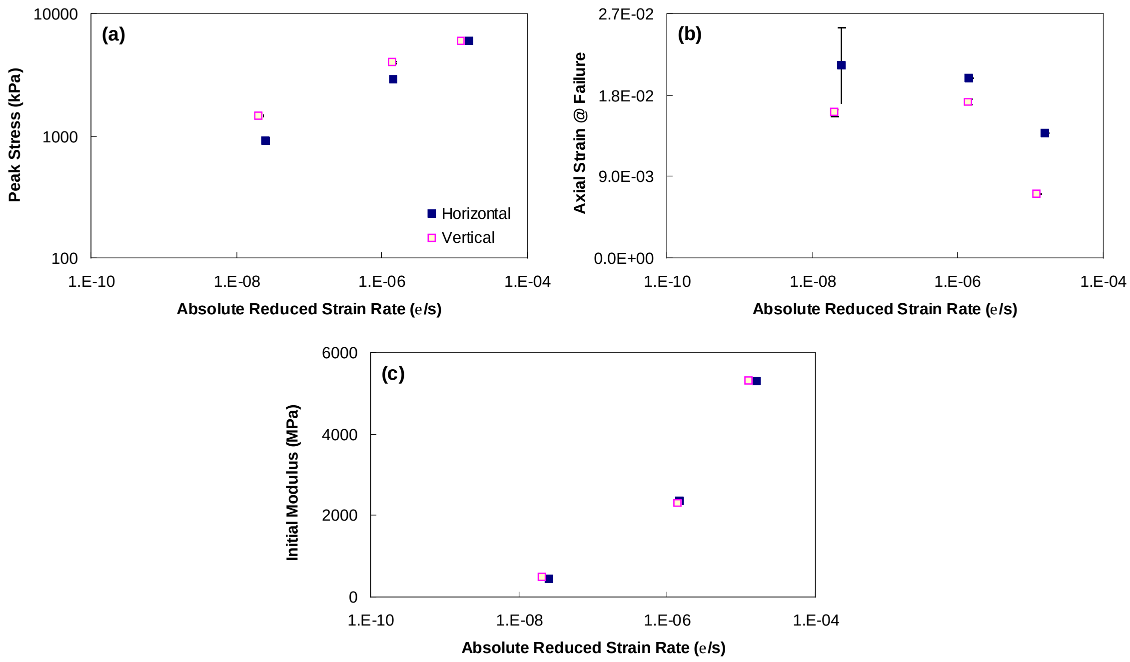

Figure 6**: Effect of anisotropy in uniaxial compression on; (a) strength, (b) axial strain at failure, and (c) initial modulus.**

5 SUMMARY AND CONCLUSIONS

The results of this experimental study have implications on flexible pavement design using most current mechanistic and mechanistic empirical design procedures. The data clearly shows that there is a difference in the compressive and tensile behaviors of asphalt concrete, both in terms of the magnitude of response and in the importance of certain mechanisms, once some strain threshold is surpassed. The exact degree of difference is primarily influenced by temperature and rate of loading, but it is likely that the material microstructure also plays an important role. Although the threshold value is unknown it appears to be some value larger than 75 $\mu\varepsilon$. Since it is not uncommon for a pavement to be subjected to strains in excess of this value, it is likely that the mechanisms observed in this paper are active in real pavement structures. Since most mechanistic and mechanistic empirical analysis techniques treat asphalt concrete as LVE for all strain levels there will likely be an error when using these techniques for pavement analysis and design. The exact degree of this error will be dependent on many site-specific factors including pavement structure, climate, and material type. However, most of these analysis tools are calibrated against in-service pavement performance data to avoid any predictive biases. As a result of this calibration process the effect of ignoring the material tendencies would be reduced. The major influence in these analysis procedures would be a reduced reliability because smearing the errors associated with misrepresentation of the material properties into the calibration function would likely produce a larger degree of predictive scatter.

The most accurate way to account for the directional dependence and anisotropic tendencies observed in the data in this paper is to develop a fully consistent analysis framework, such as a finite element model, that explicitly accounts for the active mechanisms. However, such approaches are currently limited due to their computational expense. Nevertheless, it is likely that by understanding the fundamental behaviors of asphalt concrete more clearly that better models, which are consistent with existing analysis frameworks that are computationally efficient can be developed. Such effort is the goal for ongoing investigations.

6 ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support provided by the Federal Highway Administration.

REFERENCES

American Association of State Highway Transportation Officials. 2007. *TP62-07: Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt (HMA)*. AASHTO. Washington, D.C.

Kim, Y.R., Guddati, M.N., Underwood, B.S., Yun, T.Y., Subramanian, V., Siddharth, S., and Senganal, T. 2008. *Development of Multiaxial VEPCD-FEP+*. Final Report. Federal Highway Administration. Washington, D.C.

Kim, Y. R., Guddati, M.N., Underwood, B.S., Yun, T.Y., Subramanian, V., and Heidari, A.H. 2005. *Characterization of ALF Mixtures Using the Viscoelastoplastic Continuum Damage Model.* Final Report. Federal Highway Administration. Washington, D.C.

Kim, Y.R., Seo, Y., King, M., and Momen, M. 2004. *Dynamic Modulus Testing of Asphalt Concrete in Indirect Tension Mode*. J. of Transp. Research Board. 1891. 163-173.

Kim, Y.R. 1988. *Evaluation of Healing and Constitutive Modeling of Asphalt Concrete by means of the Theory of Nonlinear Viscoelasticity and Damage Mechanics*. Dissertation. Texas A&M University, College Station, TX.

Kweon, G. and Kim, Y.R. 2006. *Determination of the Complex Modulus of Asphalt Concrete Using the Impact Resonance Test*. J. of Transp. Research Board. 1970. 151-160.

Lacroix, A.T. and Kim, Y.R., 2008. *Comparison of Acquiring Dynamic Modulus from Different Geometries and Compactions*. Proc. Trans. Research Board. Washington, D.C. January. CD-ROM.

Tschoegl, N.W. 1989. *The Phenomenological Theory of Linear Viscoelastic Behavior: An Introduction*. Springer-Verlag. Berlin.

Kaloush, K. 2001. *Simple Performance Test for Permanent Deformation of Asphalt Mixtures*. Dissertation. Arizona State University, Tempe, AZ.

Rao Tangella, S.C., J. Craus, J.A. Deacon and C.L. Monismith. 1990. *Summary Report on Fatigue Response of Asphalt Mixtures*. Report TM-UCB-A-003A-89-3. Strategic Highway Research Program. National Research Council. Washington, D.C.

Grenfell, J.R.A., Collop, A.C., Airey, G.D., Taherkhani, H, and Scarpas, A. 2008. *Deformation Characterisation of Asphalt Concrete Behaviour.* Asphalt Paving Technology. AAPT. 77. pp. 479–516.

Advanced Asphalt Technologies. 2004. *Asphalt Concrete Mixture Performance Testing and Analysis: Western Research Institute Test Sections, Interstate 15, Clark County, NV.*

Gibson, N.H. 2006. *A Viscoelastoplastic Continuum Damage Model for the Compressive Behavior of Asphalt Concrete.* Dissertation. University of Maryland, College Park, MD.