Laboratory Investigation of Anisotropic Behaviour of HMA

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ABSTRACT

The anisotropy refers to the material properties that are direction dependant. In the past, the HMA has been typically modeled as an isotropic material due to a lack of sufficient data for detailed quantification of its direction-dependency. However, it is reasonable to assert that HMA may exhibit significant anisotropic behaviour due to the major compaction direction and the resulting preferred alignment of strong axis of the aggregate particles. In order to gain basic understanding of the anisotropy of HMA, a laboratory test program has been conducted on HMA specimens with or without polymer modifiers. The method of specimen preparation to achieve samples with different orientations between the specimen compaction direction and the axial load in the triaxial testing is described. The confined triaxial compression test is used to obtain mechanical properties of various HMA specimens with three orientation angles (0, 45, and 90 degrees) between the direction of the specimen compaction and the direction of the axial load direction in the triaxial test. The mechanical properties investigated in the laboratory test program include the compressive strength (defined as the peak deviator stress), the modulus of elasticity (defined as initial portion of the stress-strain curve), the strain at the peak strength (used as an indication of the ductility of the mix), and the toughness of the mix (determined as the area under the stress-strain curves). Also, a comprehensive testing program using the repeated triaxial testing procedure is carried out on the specimens with three orientation directions to investigate the accumulation of permanent deformation under repeated loadings. This paper presents pertinent test results and exams the significance of anisotropy. Based on the experimental results of the laboratory test program, the anisotropic behaviour of HMA is found to be significant. Therefore, in order to accurately predict the stress and strain regimes in the pavement layers under traffic load, the HMA should be modeled as an anisotropic media. Predictions of permanent deformation (rutting) require proper consideration of material anisotropy as well.

INTRODUCTION

The characterization and modeling of the anisotropic properties of soils have been widely explored in geomechanics and geotechnical engineering. However, very few research studies have focused on the characterization and modeling of the anisotropic properties of the asphalt concrete mixtures. It has been realized that the anisotropy of HMA materials greatly depends on specimen preparation and testing conditions (1). The behavior is further influenced by the magnitude of stresses and strains induced within the HMA material and the rate of load application. The mechanical behavior of many bound materials such as asphalt concrete mixtures is anisotropic in nature (2). However, the majority of the current mechanical tests and analytical models for asphalt concrete mixtures are based on the assumption of isotropic material properties. No known pavement structural response model based on layered theory considers the anisotropy of the asphalt concrete materials (3, 4). Most known models are based on the linear elastic or linear viscoelastic theory. In the linear elastic theory, the asphalt concrete material is assumed to be homogenous, isotropic and linear elastic. The viscoelastic theory considers the time rate of stresses and strains in the asphalt concrete layer, with the similar assumptions of homogeneity and isotropy.

This paper presents a laboratory program to investigate anisotropic behaviour of HMA under both static and repeated loading conditions. The mechanical properties investigated in the laboratory test program include the compressive strength (defined as the peak deviator stress), the modulus of elasticity (defined as initial portion of the stress-strain curve), the strain at the peak strength (used as an indication of the ductility of the mix), and the toughness of the mix (determined as the area under the stress-strain curves). Also, a comprehensive testing program using the repeated triaxial testing procedure is carried out on the specimens with three orientation directions to investigate the accumulation of permanent deformation under repeated loadings. This paper presents pertinent test results and exams the significance of anisotropy. Based on the experimental results of the laboratory test program, the anisotropic behaviour of HMA is found to be significant.

BACKGROUND

Anisotropy refers to the material properties which are direction dependent. The asphalt concrete material is a mixture of aggregates and asphalt binders. As a result, the compressive strength of the asphalt concrete material is derived from the resistance of the aggregate to the applied load, provided by the aggregate interlocking, and the stiffness of the asphalt binder. Since the aggregate orientation could be influenced by compaction, the resistance to the applied loads provided by the aggregate interlocking could be different. Therefore, the asphalt concrete material properties in one direction could be different from those in other directions.

Although asphalt concrete may be considered as anisotropic material Wang et al (1), for simplification purposes, considered only cross anisotropy or orthotropy in their effort to characterize the properties of asphalt concrete mixtures. Wang et al (1) performed triaxial laboratory testing on cubic asphalt concrete specimens of 4 inch in lateral length, using a multistage loading procedure. The multistage loading procedure includes isotropic compression (IC) followed by triaxial compression (TC), followed by triaxial extension (TE), followed by simple shear (SS), followed by conventional triaxial compression (CTC), and finally followed by conventional triaxial extension (CTE). Results from the CTC and the CTE tests were used to calculate the magnitudes of the elastic modulus in the vertical direction (E_v) and in the horizontal direction (E_h). It was found that the vertical elastic modulus was usually two to three times larger than the horizontal elastic modulus. The IC test results showed that the asphalt concrete compacted in the field exhibits anisotropic behaviour. The strains induced in the vertical direction were different than those induced in the horizontal directions. Wang et al (1) concluded that a larger shear stress may develop in anisotropic materials due to traffic load, thus causing more pronounced shear flow and the accompanied rutting.

The effects of anisotropy on the compressive properties of asphalt concrete mixtures have been investigated by Mamlouk et al (5) by carrying out displacement controlled compression tests on the vertical and horizontal cores. Test results showed that there were no significant variations in the compressive strength and the axial strain at failure between the vertical and horizontal orientations. Results also showed that the horizontal cores exhibited higher initial elastic modulus than the vertical cores. However, Mamlouk et al mentioned that these results could have been affected by specimen preparation methods, testing conditions, and specimen size.

Masad et al (5) used the aggregate particle orientation as a significant property of the asphalt mixture internal structure to assist in the characterization of the anisotropy of asphalt concrete mixtures. The study showed the significant role played by the aggregate orientation in the characterization of the anisotropic response of the asphalt concrete materials.

Garg et al (6) analyzed the asphalt concrete strain responses from the slow-rolling response tests. Test results showed that significant permanent strains were measured, especially in the transverse direction. Garg's study (6) showed that there was a difference in the response of the asphalt concrete material in different directions.

Findings of these studies indicate that the pavement design based on isotropic elasticity analysis may underestimate the shear stresses and tensile stresses that are related to permanent deformation and fatigue cracking assessment. Therefore, one of the main purposes of this study is to investigate the static and dynamic response of the specimens of the asphalt concrete mixtures cored in different directions.

LABORATORY EXPERIMENTAL PROGRAM

This section provides information about the materials used in this study, the experimental procedures used to produce the required hot mix asphalt concrete samples, and the test program.

Materials

A mix of two different types of aggregate was used in preparing the hot mix asphalt concrete specimens for the test program. The coarse aggregate (retained on sieve #4) was limestone brought from Akron Crushed Limestone Company in Akron, Ohio. The fine aggregate (passing sieve #4) was sandstone brought from Allied Corporation Inc. in Massillon, Ohio. Aggregate gradation used was according to ODOT requirements for heavy traffic (Type-1H). Two asphalt binders were used in preparing the HMA specimens: the virgin asphalt binder (PG 58-28), and the 5% SBS (Styrene Butadiene Styrene) modified asphalt binder (PG 76-22). Based on Marshal mix test results, the optimum binder content of 5.9% was adopted.

Specimen Preparation Method

A special mold was designed and built for the purpose of compacting loose aggregate/binder into compacted specimens. The mold consists of three layers, with each layer being three inches high. A one-ton static roller compactor was used to compact about 400 lb of aggregate and 25 lb of binder loose mix into a density corresponding to a target air void of 3.5%. The compaction was done in three separate layers to assure that the target air void after compaction is uniform throughout the mix. The mixing procedure is as follows: (1) sieving, washing, and drying the aggregate, (2) blending the aggregate according to the gradation curves, (3) heating the aggregate at 330 °F for 3 hours, (4) heating the asphalt binder at 350 °F for 2-3 hours to produce a viscosity of 175 ± 20.5 cP before mixing with the aggregate, (5) mixing the aggregate and asphalt binder together according to the calculated weights for each layer of the mold, and (6) compacting the loose mix using the one-ton static roller compactor for each layer separately.

After completing the mixing and compaction procedure, the compacted asphalt concrete slab was left for 24 hours in the mold to allow it to cool down to the room temperature. Then, a coring machine with a 4 inches diameter bid was used to extract cores in three orientations: vertical, horizontal and diagonal at 45°. Since the coring machine used in the core extraction process did not have the ability to extract cores in the diagonal direction, a separate mold with a 45° inclined surface was built for that purpose. The compacted slab is placed on the 45° inclined surface of this mold then the coring machine extracts the cores vertically producing cores with the 45° inclination angle.

Test Program

The test program for the displacement controlled compression test is described in two flow charts presented by Figures 1. Specimens were conditioned for three hours at a temperature of 104 °F prior to testing. The Material Testing System (MTS) Closed-Loop Servo Hydraulic System, Model 810 was used. Two deformation rates were used in the test program: 0.4 in/min and 0.04 in/min, representing high and low strain rates, respectively. Two confining pressures were used when testing the unmodified asphalt concrete mixtures, while three confining pressures were used when testing the modified asphalt concrete mixtures.

To determine the permanent deformation characteristics of asphalt concrete materials a repeated dynamic load test for several thousand repetitions is carried out. The cumulative permanent deformation over the given loading period is measured. In this study, the repeated load tests were performed on asphalt concrete samples cored in three directions at a test temperature of 104 °F, as shown in Table 1. A haversine pulse load was applied (one load pulse per second), with a loading time of 0.1 seconds and a rest time of 0.9 seconds. Each test was conducted for up to 50,000 load cycles.

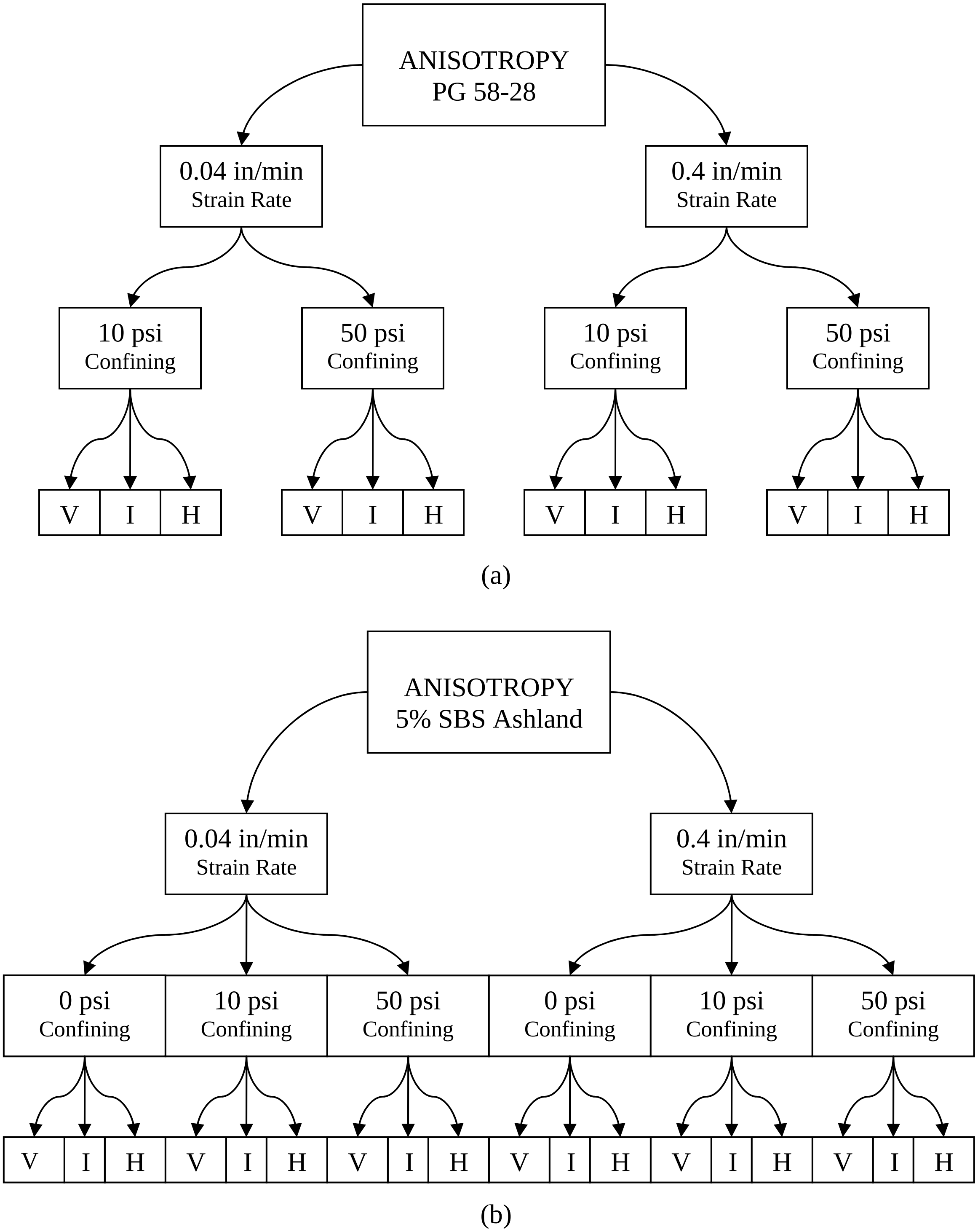

FIGURE 1 Diagram depicting the experimental program conducted to investigate the anisotropy of (a) HMA using PG 58-28 binder, and (b) HMA using PG 76-22 binder.

TABLE 1 Stress Values Used in the Permanent Deformation Tests for Vertical, Inclined and Horizontal Asphalt Concrete Specimens

Core Orientation	Confining Pressure (psi)	Deviator Stress q (psi)	Mean Stress p (psi)	Stress Level q/p	No of Load Cycles
Vertical Orientation	10	2.73	10.92	0.25	20,000
	30	8.18	32.72	0.25	30,000
	40	10.91	43.64	0.25	40,000
	50	13.64	54.56	0.25	50,000
	10	6.00	12.00	0.50	50,000
	20	12.00	24.00	0.50	50,000
	30	18.00	36.00	0.50	50,000
	40	24.00	48.00	0.50	50,000
Inclined Orientation	10	2.73	10.92	0.25	50,000
	40	10.91	43.64	0.25	50,000
	10	6.00	12.00	0.50	50,000
	40	24.00	48.00	0.50	50,000
Horizontal Orientation	10	2.73	10.92	0.25	50,000
	40	10.91	43.64	0.25	50,000
	10	6.00	12.00	0.50	50,000
	40	24.00	48.00	0.50	50,000

LABORATORY TEST RESULTS AND DATA ANALYSIS

Displacement controlled compression test results as well as repeated triaxial test results are shown and discussed in the following section. The discussion highlights the effect of core orientation on the compressive strength, the modulus of elasticity, toughness, strain at the peak strength, and the permanent deformation.

Anisotropy Effect on the Asphalt Concrete Mixtures under Static Loading

HMA Using PG 76-22 Binder (SBS modified)

Figure 2 shows the effect of core orientation on the compressive strength of the modified asphalt concrete samples tested at two deformation rates and three confining pressures. The zero angle represents the cores with the vertical orientation, and the 90° angle represents the cores with the horizontal orientation. The figure shows that the vertically cored asphalt concrete samples exhibited the highest compressive strength, followed by those cored in the inclined direction, followed by the horizontally cored samples.

Figure 3 shows the core orientation effect on the modulus of elasticity tested at two deformation rates and three confining pressures. The figure shows the same trends as that for the compressive strength. At zero confining pressure, there was no effect of the core orientation on the elastic modulus. The anisotropy in the elastic modulus was more pronounced at higher levels of confinement. The vertically cored asphalt concrete samples exhibited the highest modulus of elasticity, followed by those cored in the inclined direction, followed by the horizontally cored samples.

Figure 4 shows the core orientation effect on the values of the strain at the peak strength tested at two deformation rates and three levels of confinement. The values of the strain at the peak strength were used as an indication for the ductility of the mixtures. The mixture is considered to have more ductility with higher values of the strain at the peak strength. Figure 4 shows that at zero confining pressure, there was no significant effect of the core orientation on the strain at the peak strength. At higher confining pressures, a significant increase in the ductility of the vertically cored samples over the other two orientations was noticed, except for one case which could be considered as an outlier. The inclined cores and the horizontal cores, on the other hand, exhibited almost the same ductility. This indicates that the asphalt concrete shows more ductility when loaded in the vertical direction compared to the other two directions.

Figure 5 depicts the effects of core orientation on the toughness of the specimens tested at two deformation rates and three levels of confinements. The figure shows that at zero confinement, there was no effect of the core orientation on the toughness of the mix. The anisotropic behavior in terms of toughness was more significant at high confining pressures. The asphalt concrete specimens cored in the vertical direction exhibited the highest toughness, followed by those cored in the inclined direction, followed by those cored in the horizontal direction.

HMA Using PG 58-28 (unmodified binder)

For the specimens of the HMA using unmodified binder (PG 58-28), Figure 6 shows the core orientation effect on the compressive strength of the samples tested at two deformation rates and two confining pressures. The figure shows that the vertically cored asphalt concrete samples exhibited the highest compressive strength, followed by those cored in the inclined direction, followed by the horizontally cored samples. The anisotropic behavior was more significant at 0.4 in/min deformation rate.

Figure 7 presents the core orientation effect on the modulus of elasticity. The figure shows that there was no significant difference in the elastic modulus between the three orientations, except in one case at the high deformation rate and high confining pressure.

Figure 8 shows the core orientation effect on the values of the strain at the peak strength. There was no clear trend showing any significant effect of the core orientation on the ductility of the conventional unmodified asphalt concrete specimens.

Figure 9 shows the effects of core orientation on the toughness of unmodified HMA. The figure shows that at the slow deformation rate, there was no significant effect of the core orientation on the toughness of the mix. The anisotropic behavior in terms of toughness was more significant at the high deformation rate. The asphalt concrete specimens cored in the vertical direction exhibited the highest toughness, followed by those cored in the inclined direction, followed by those cored in the horizontal direction.

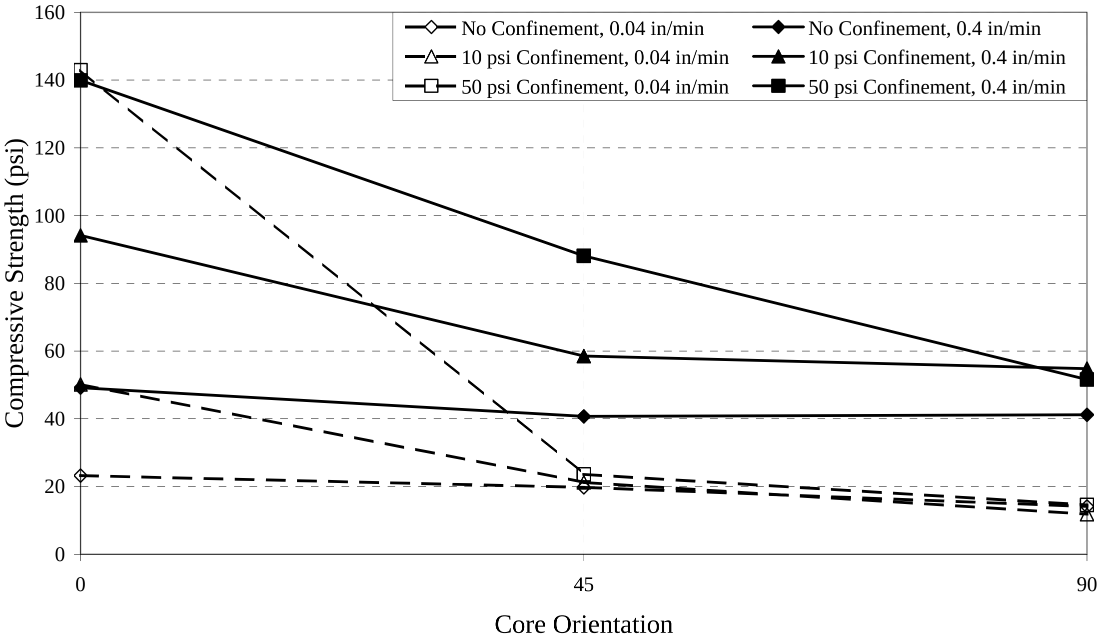

FIGURE 2 Core orientation effect on the compressive strength of asphalt concrete mixtures containing 5% SBS modified binder (PG 76-22).

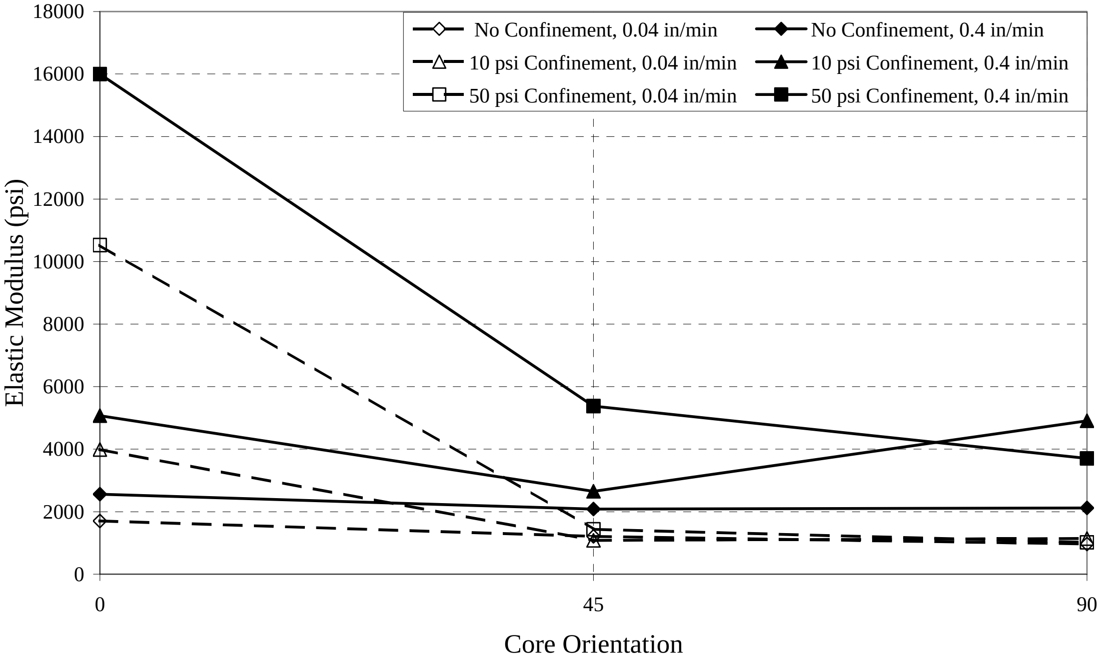

FIGURE 3 Core orientation effect on the modulus of elasticity of asphalt concrete mixtures containing 5% SBS modified binder (PG 76-22).

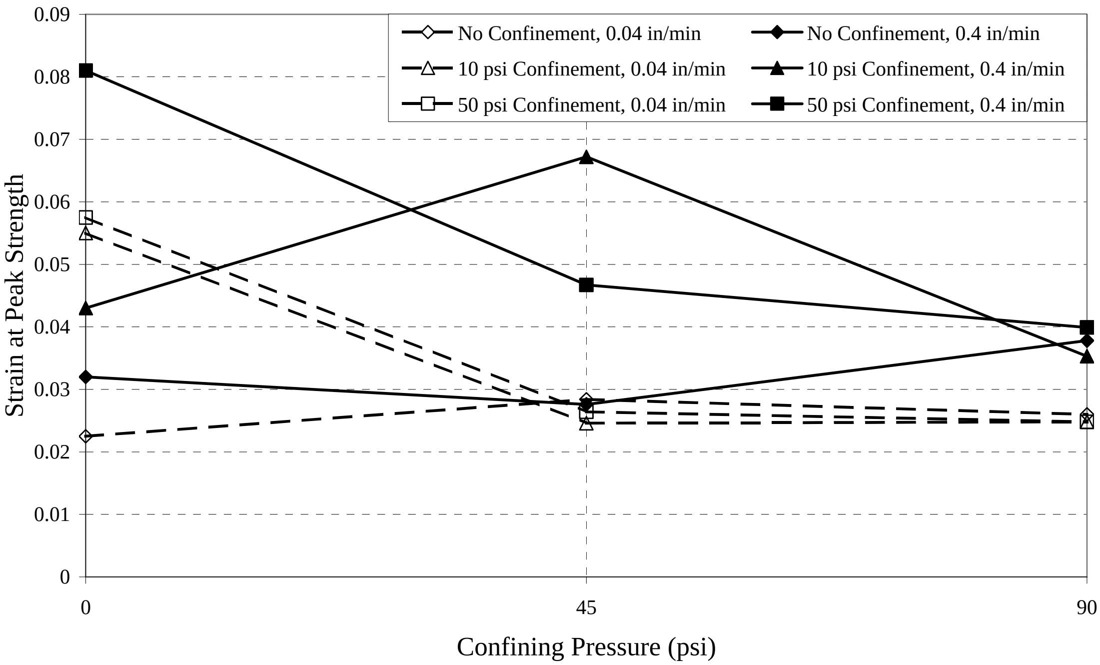

FIGURE 4 Core orientation effect on strains at peak strength of asphalt concrete mixtures containing 5% SBS modified binder (PG 76-22).

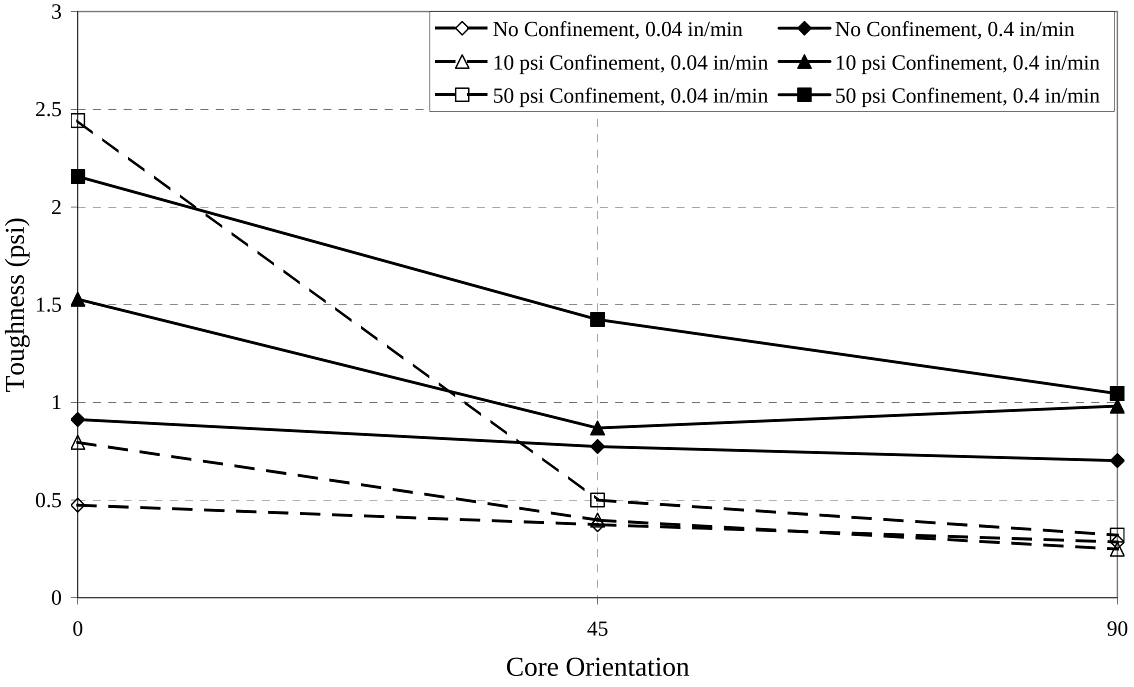

FIGURE 5 Core orientation effect on the toughness of asphalt concrete mixtures containing 5% SBS modified binder (PG 76-22).

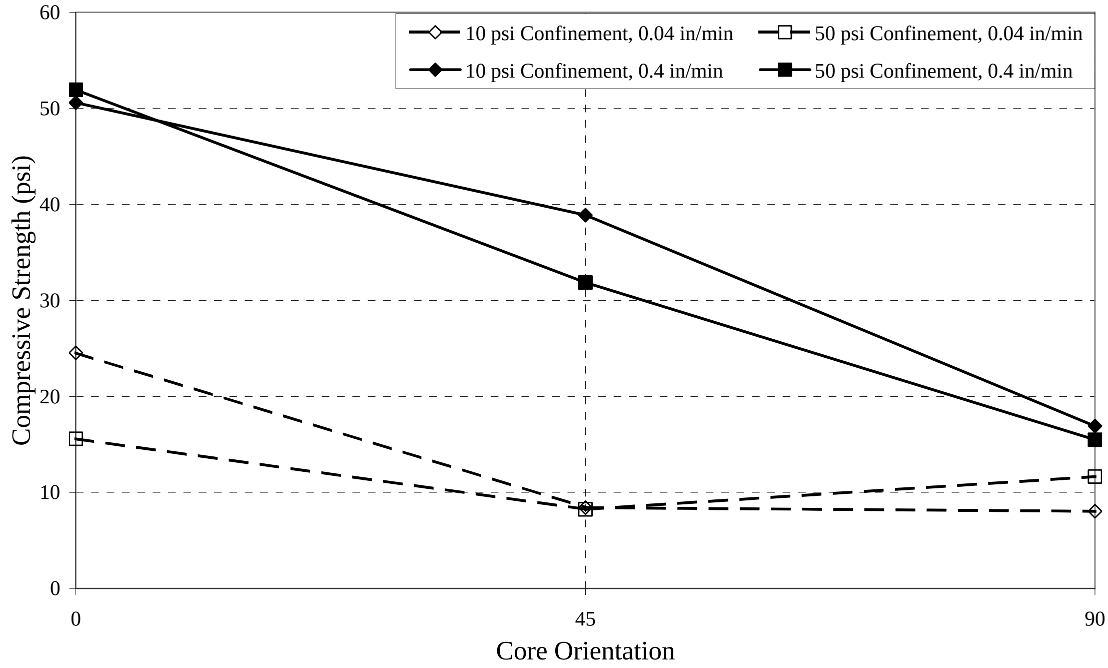

FIGURE 6 Core orientation effect on the compressive strength of the unmodified asphalt concrete mixtures.

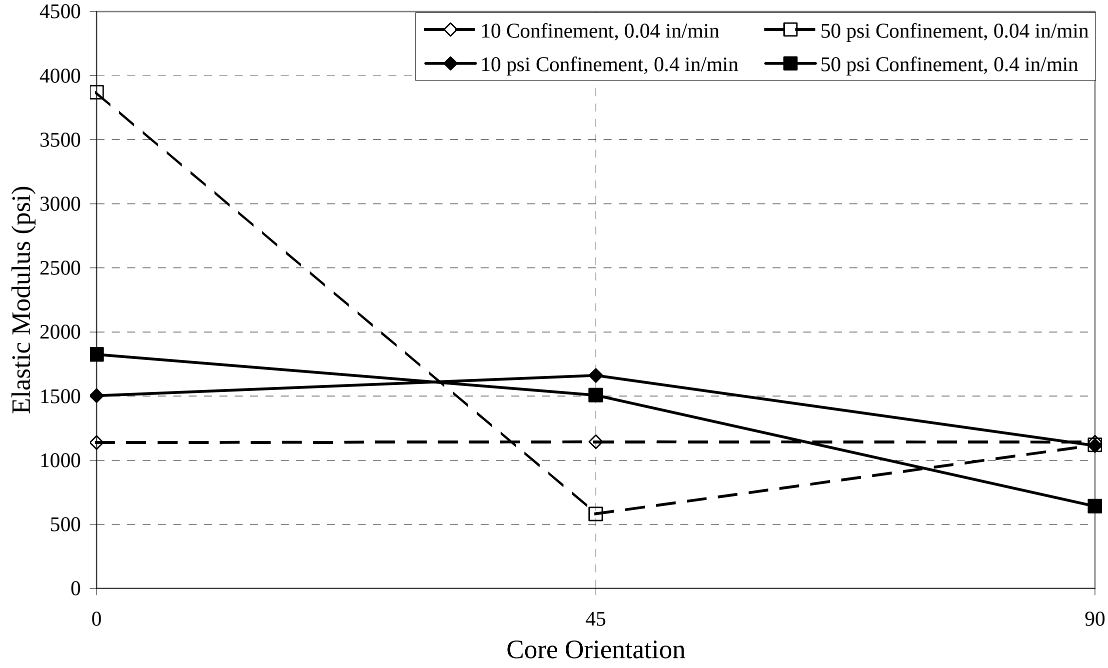

FIGURE 7 Core orientation effect on the modulus of elasticity of the unmodified asphalt concrete mixtures.

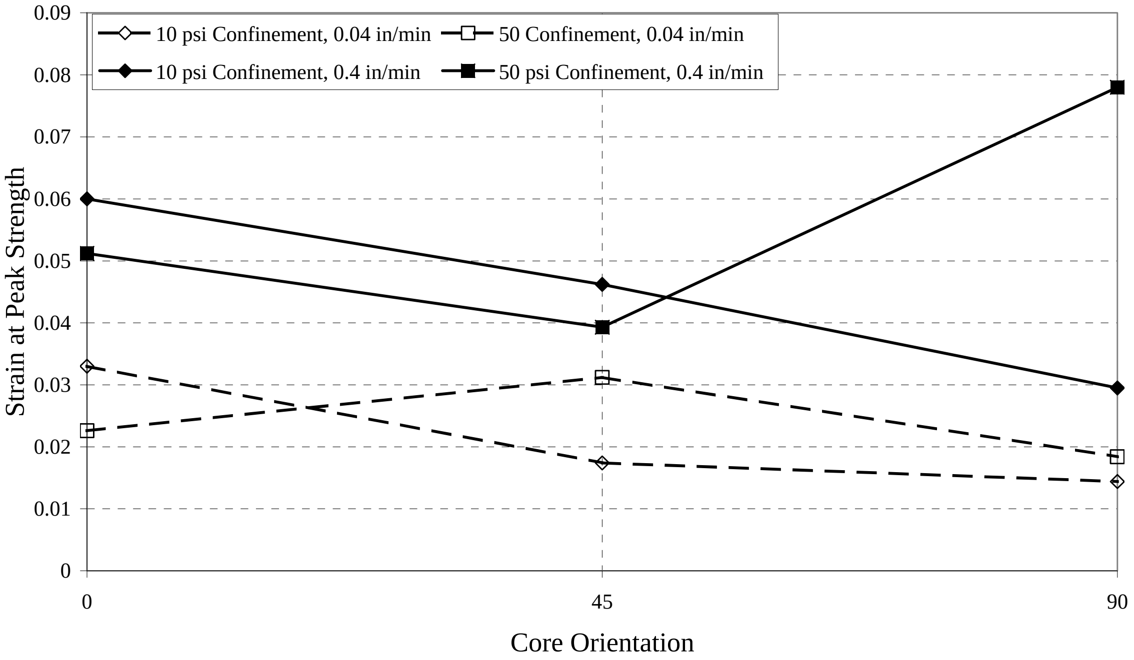

FIGURE 8 Core orientation effect on the strains at peak strength of the unmodified asphalt concrete mixtures.

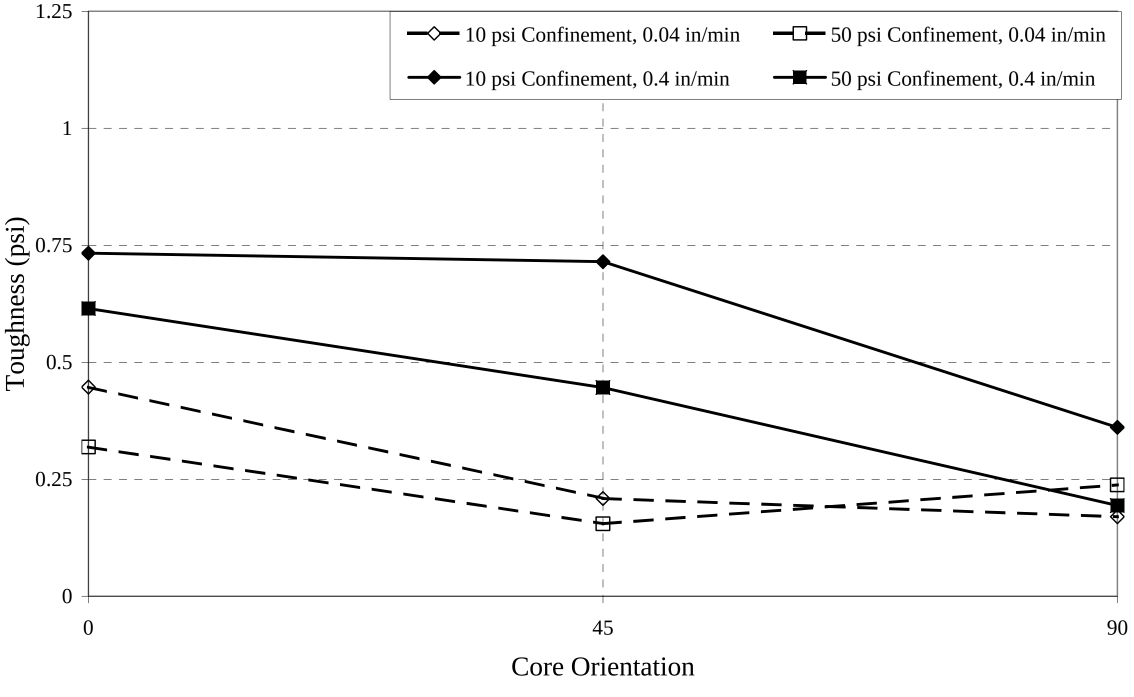

FIGURE 9 Core orientation effect on the toughness of the unmodified asphalt concrete mixtures.

Anisotropy Effect on the Asphalt Concrete Mixtures under Repeated Loading

The permanent strains exhibited by HMA specimens with different orientations are plotted against the number of load cycles to show the response of asphalt concrete specimens subjected to rotation of principal stress directions during dynamic triaxial loading. Figures 10 and 11 show, respectively, the responses to repeated loading of the asphalt concrete specimens cored in the three orientations at two stress levels of 0.25 and 0.50, and two confining pressures of 10 psi and 40 psi. At both stress levels and at the low confining pressure of 10 psi, it can be seen that the horizontally cored asphalt concrete specimens exhibited the highest amount of permanent deformations accumulation, followed by the asphalt concrete specimens cored in the inclined direction, followed by the vertically cored asphalt concrete specimens.

Increasing the confining pressure to the value of 40 psi, with the corresponding adjustment to the axial load, completely changes the results, as shown in Figure 11. This figure shows that there was no clear trend of the difference in the response of the three orientations to the repeated loading at both stress levels.

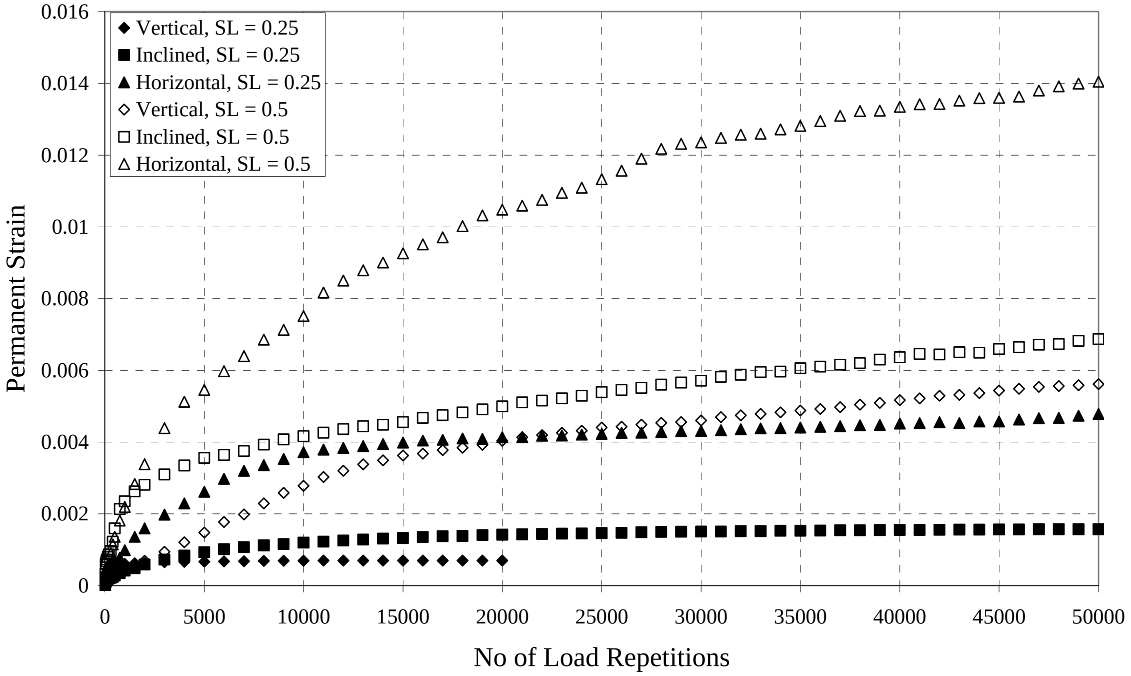

FIGURE 10 Permanent deformation versus no. of load repetitions for tests conducted at confining pressure = 10 psi.

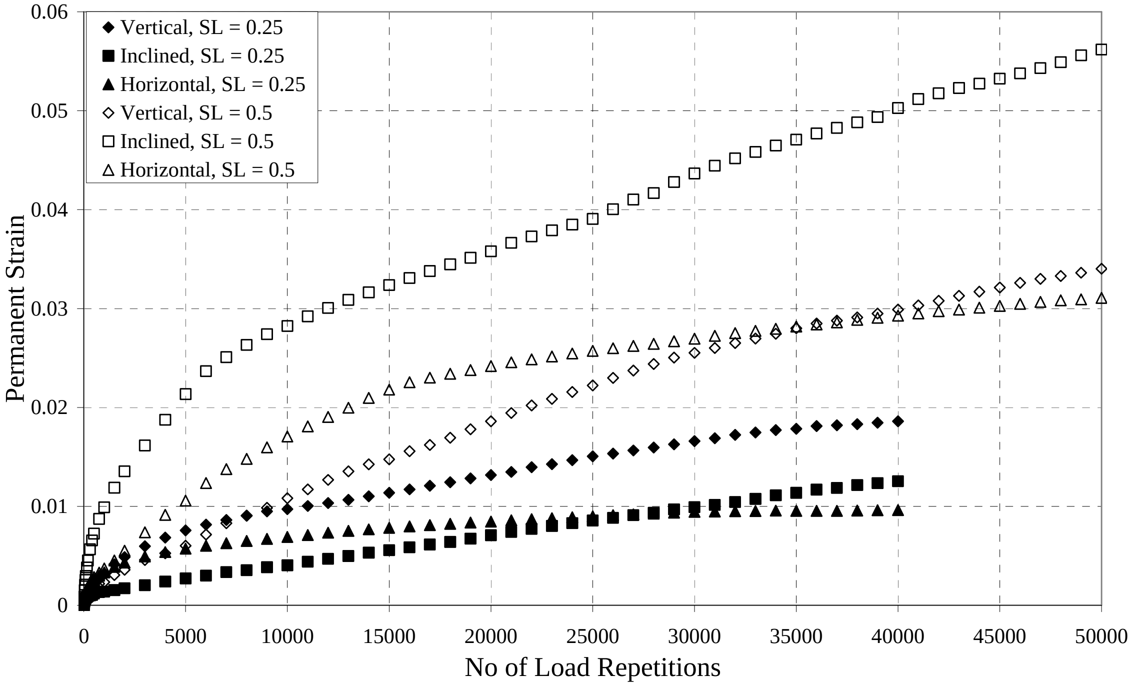

FIGURE 11 Permanent deformation versus no. of load repetitions for tests conducted at confining pressure = 40 psi.

OBSERVATIONS AND CONCLUSIONS

The following observations can be drawn from this study:

- The behavior of both types of asphalt concrete mixtures was found to be direction dependent.
- The anisotropic behavior of the asphalt concrete mixtures could be related to the anisotropy in the orientation of the aggregate particles inside the asphalt concrete mix. As a result of the vertical force generated by the compaction process, the aggregate particles embedded in the asphalt concrete mix tend to rotate to the direction parallel to the horizontal direction (2). This change in the aggregate orientation as a result of the compaction may have resulted in more resistance to the loads applied in the vertical direction due to aggregate interlocking. It could be for the same reasons that the resistance of the asphalt concrete mixtures to the loads applied in the horizontal direction was reduced.
- The anisotropy of the asphalt concrete mixtures containing 5% SBS modified binder (PG 76-22) was more pronounced at higher levels of confinement. The anisotropy of the unmodified asphalt concrete mixtures containing unmodified binder (PG 58-28), on the other hand, was more significant at higher deformation rates.
- Both static compression testing and the dynamic testing provided the same observations in terms of anisotropy of the asphalt concrete material. The vertically cored asphalt concrete samples exhibited the highest resistance to the applied loads (static and dynamic), followed by the specimens cored in the inclined direction, followed by those cored in the horizontal direction. These observations were only true at the low applied axial loads for both types of asphalt concrete mixtures used in both tests.

- Based on the repeated load tests results, a significant difference was observed for asphalt concrete mixtures cored in different directions. This difference in the response may be related to the effect of the compaction process. The compaction effort on the vertical direction resulted in anisotropy in the distribution and orientation of the aggregate particles as well as the voids. The anisotropy in the distribution and orientation in the aggregate particles and the voids resulted in anisotropy in the responses of the asphalt concrete materials to the applied repeated loads. The anisotropy of the shape and angularity of the aggregate particles may also have contributed to the observed anisotropy of the mechanical properties. Therefore, it would be of a great benefit if more investigations are carried out to evaluate the effect of the aggregate particles distribution, orientation, shape, and angularity on the anisotropic response of the asphalt concrete materials to the repeated loading.
- To provide the best design practice, the anisotropic response of HMA to the applied loads should be considered in the analysis methods.

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