Comparison of Axial and Diametral Resilient Stiffness of Asphalt-Aggregate Mixes

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The stiffness of asphalt-aggregate mixes is important in determining how well a pavement performs, and is an essential property for analyzing pavement response to traffic loading. A study for stiffness determination of asphalt-aggregate mixes was conducted as a part of Project A-003A of the Strategic Highway Research Program (SHRP). Its purpose was to evaluate the sensitivity of the axial (compressive) and diametral (indirect tensile) resilient stiffness to mix and test variables and to compare the axial and diametral resilient stiffness of 16 mixes tested under various temperatures, stress levels, and loading frequencies. Results of this study indicate that both axial and diametral resilient stiffnesses are sensitive to mix and test variables, including asphalt type, aggregate type, air-void content, and temperature. However, axial and diametral testing of mixes yield different estimates of their resilient stiffnesses. Diametral resilient stiffness computed using an assumed Poisson's ratio of 0.35 generally exceeds axial resilient stiffness by an average of approximately 35 to 45 percent. SHRP Project A-003A experience suggests that the indirect tension test is not accurate for relatively weak specimens at temperatures as high as 60°C (104°F), and tension may not be reliable even at moderately high temperatures [40°C (140°F)] due to excessive vertical permanent deformation. The influence of mix and testing variables on resilient stiffness may be different depending on whether loading is in axial compression or indirect tension. By inference, differences in mix design and structural pavement design may result depending on the type of testing system used to estimate mix stiffness.

The stiffness of asphalt-aggregate mixes is important in determining how well a pavement performs and is an essential property for the analysis of pavement response to traffic loading. Although fatigue and permanent deformation tests can often be used to measure stiffness under conditions similar to those experienced by paving mixes in service, stiffness testing complements strength testing and provides essential information when results of strength tests are unavailable. Accordingly, an independent study for stiffness testing of asphalt-aggregate mixes was conducted in Project A-003A of the Strategic Highway Research Program's (SHRP's) asphalt research endeavor. Described herein are the results of axial and diametral resilient stiffness tests performed on 16 mixes. Specific objectives of this study included evaluation of the sensitivity of the axial and diametral resilient stiffnesses to mix and test variables and comparison of the axial and diametral resilient stiffness values for similar mixes tested under the same conditions. The diametral resilient stiffness value is of particular significance in this study because NCHRP investigators (*1*) recommended its use in an asphalt-aggregate mix analysis system (AAMAS) for characterization of mix stiffness at moderate temperatures 5°C to 40°C (41°F to 104°F).

LABORATORY TEST PROGRAM

This study of stiffness test methodologies was primarily a laboratory investigation, which included evaluation of mixes containing two core SHRP Materials Reference Library asphalts and two core aggregates. A total of 16 different mixes (combination of 2 asphalts, 2 aggregates, 2 asphalt contents and 2 air void contents) was evaluated in axial and diametral loading for a range of temperatures, stress levels, and loading frequencies (*2*). Table 1 summarizes the mix and test variables and identifies the characteristics of asphalts and aggregates used.

Axial and diametral resilient stiffness tests were conducted in accordance with ASTM D 3497 (Test Method for Dynamic Modulus of Asphalt Mixtures) and D 4123 (Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures), respectively. Only total resilient stiffness (M_R) is reported in this paper.

Because resilient stiffness testing is considered nondestructive, each specimen was subjected to the full range of loading conditions at each of the test temperatures, stress levels, and loading frequencies. The high and low stress levels used during testing were adjusted according to test temperature, not only to ensure a reasonable strain reading under applied stress, but also to ensure that specimens did not experience excessive damage at the higher temperatures. Table 2 identifies the average target stress levels used at the different temperatures.

A total of 512 (16 mixes and 16 test conditions with full replication) stiffness tests was performed for the axial loading conditions, and 384 (16 mixes and 12 test conditions with full replication) for the diametral loading conditions. For both test types, specimens were fabricated using the Triaxial Institute kneading compactor. Aggregate gradation, identical for both test programs, is given in Table 3.

TEST RESULTS

Table 4 summarizes the average axial and diametral resilient stiffness values for the various materials and test conditions. The average stiffness values were computed by first partitioning the data set for each temperature according to the independent variable being

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TABLE 1 Significant Mix and Test Variables for Stiffness Study

<table>
<tr><td rowspan="3">Asphalts:</td><td colspan="8">2 - MRL[1] Core asphalts</td></tr>
<tr><td>Type</td><td>Grade</td><td colspan="6">Penetration Index (PI)</td></tr>
<tr><td>AAK-1
AAG-1</td><td>AC-30
AR-4000</td><td colspan="6">-0.5
-1.4</td></tr>
<tr><td>Aggregates:</td><td colspan="8">2 - MRL Core aggregates
RB - Watsonville granite, crushed, rough surface texture
RL - Chert, partially crushed, smooth surface texture</td></tr>
<tr><td rowspan="5">Asphalt contents: (percent by wt. of aggregates)</td><td colspan="8">2 - optimum[2] and high depending on asphalt and aggregate type</td></tr>
<tr><td colspan="4">AAK-1</td><td colspan="4">AAG-1</td></tr>
<tr><td colspan="2">RB</td><td colspan="2">RL</td><td colspan="2">RB</td><td colspan="2">RL</td></tr>
<tr><td>Opt.</td><td>High</td><td>Opt.</td><td>High</td><td>Opt.</td><td>High</td><td>Opt.</td><td>High</td></tr>
<tr><td>5.1</td><td>5.7</td><td>4.3</td><td>5.0</td><td>4.9</td><td>5.5</td><td>4.1</td><td>4.8</td></tr>
<tr><td>Air void contents:</td><td colspan="8">2 - 4±1 and 8±1 percent</td></tr>
<tr><td>Stress levels:</td><td colspan="8">2 - low and high varies with temperature</td></tr>
<tr><td>Temperature:
Axial tests
Diametral tests</td><td colspan="8">
4 - 0°, 20°, 40° and 60°C
3 - 0°, 20° and 40°C</td></tr>
<tr><td>Test frequency:</td><td colspan="8">2 - 1 and 0.5 Hz, pulse loading, 0.1 seconds loading time</td></tr>
<tr><td>Number of replicates:</td><td colspan="8">2</td></tr>
<tr><td>Specimen size:
Axial tests
Diametral tests</td><td colspan="8">
101.6 mm diameter, approximately 203.2 mm high
101.6 mm diameter, approximately 63.5 mm high</td></tr>
<tr><td>Total number of mixes:</td><td colspan="8">16</td></tr>
<tr><td>Total No. of tests:
Axial stiffness
Diametral Stiffness</td><td colspan="8">
512 (16 mixes, 16 test conditions, full replication)
384 (16 mixes, 12 test conditions, full replication)</td></tr>
</table>

[1] SHRP Materials Reference Library

[2] Optimum by Hveem mix design method, High = optimum+0.6%

considered and then obtaining average values for all other variables. Comparison of the axial and diametral stiffness values indicates that on average the diametral stiffness is about 35 to 45 percent greater than the axial stiffness. Table 5 summarizes values for the ratio of the average resilient stiffness values measured by axial and diametral tests for the various mix and test variables. Examination of these data indicates the following:

1. At lower temperatures, specimens containing asphalt AAK-1 exhibit lower axial and diametral stiffness values than specimens containing asphalt AAG-1. At higher temperatures, specimens containing asphalt AAK-1 have higher axial stiffness values and lower diametral stiffness values than specimens containing asphalt AAG-1. Because of the differences in the temperature susceptibility characteristics of the two asphalts, it would have been expected that

TABLE 2 Target Average Stress Levels Used for Different Temperatures

Temperature	Axial		Diametral	
	Low Stress, kPa	High Stress, kPa	Low Stress, kPa	High Stress, kPa
0°C	211	419	186	357
20°C	107	213	97	188
40°C	56	109	47	95

TABLE 3 Aggregate Gradation Used

Sieve Size	Percent Passing by Weight	ASTM Spec. (D 3515)
25.0 mm	100	100
19.0 mm	95	90-100
12.5 mm	80	-
9.50 mm	68	56-80
4.75 mm	48	35-65
2.36 mm	35	23-49
1.18 mm	25	-
600 μm	17	-
300 μm	12	5-19
150 μm	8	-
75 μm	5.5	2-8

the stiffness of mixes containing asphalt AAK-1 would be higher at the higher temperature in both tests.

2. Specimens with the high asphalt content generally show higher axial resilient stiffness values than those with the low asphalt content. For diametral resilient stiffness the effect of asphalt content is reversed: specimens with the high asphalt content show lower stiffness than those with the low asphalt content.

3. Specimens containing RB aggregate show higher axial resilient stiffness values than those containing RL aggregate, except at 0°C (32°F) where the stiffness values are about the same. On the other hand, diametral stiffness values for specimens containing RB aggregate are lower than for those containing RL aggregate, except at 0°C (32°F).

4. Axial stiffness is more sensitive to air-void content than diametral stiffness.

The axial and diametral stiffness were also analyzed statistically with a general linear model (GLM) formulation as summarized in the next section.

TABLE 4 Effect of Mix and Testing Variables on Average Axial and Diametral Resilient Stiffness Values

Variable	Level	Average Axial Resilient Stiffness, MPa			Average Diametral Resilient Stiffness, MPa		
		0°C	20°C	40°C	0°C	20°C	40°C
Asphalt Type	AAK-1	11,868	3,333	545	16,215	4,223	667
	AAG-1	17,940	6,224	524	24,495	8,556	876
Asphalt Content	Optimum	14,697	4,575	538	21,390	7,176	849
	High	15,111	4,982	531	19,320	5,548	697
Aggregate Type	Granite (RB)	15,111	5,223	587	21,597	6,093	718
	Chert (RL)	14,697	4,333	483	19,113	6,652	828
Air Voids	Low	17,733	6,044	704	23,184	7,314	952
	High	12,075	3,512	366	17,457	5,423	591
Stress Level	Low	14,904	4,816	545	20,355	6,541	814
	High	14,904	4,740	531	20,355	6,210	731
Frequency	Low	14,835	4,685	524	20,217	6,320	807
	High	14,973	4,871	545	20,493	6,424	738
Repeats	First	15,042	4,713	531	19,941	6,044	773
	Second	14,766	4,844	538	20,769	6,700	773
Average		14,904	4,775	538	20,355	6,376	773

TABLE 5 Ratio of Resilient Stiffness Values for Axial and Diametral Tests

Variable	Ratio	0°C		20°C		40°C	
		Axial	Diametral	Axial	Diametral	Axial	Diametral
Asphalt Type	AAK-1 /AAG-1	0.66	0.66	0.54	0.49	1.03	0.76
Asphalt Content	Low/High	0.97	1.11	0.92	1.29	1.01	1.22
Aggregate	RB/RL	1.03	1.13	1.21	0.91	1.22	0.87
Air Voids	Low/High	1.47	1.32	1.72	1.34	1.93	1.61
Stress	Low/High	1.00	1.00	1.02	1.05	1.03	1.11
Frequency	Low/High	0.99	0.99	0.96	0.98	0.95	1.09
Repeats	First/Second	1.02	0.96	0.97	0.90	0.98	1.00
Ratio of average diametral to axial resilient stiffness		1.37		1.35		1.45	
Percent difference		37		35		45	

Statistical Analysis of Test Results

The main purpose of the statistical analysis was to determine the sensitivity of stiffness to mix and test variables. Two responses were examined, the logarithm of the resilient stiffness and the ratio of the diametral stiffness to the axial stiffness. Independent variables in the GLMs included all seven of the mix and test variables, together with all two-factor interactions among them. Accordingly, a linear model of the following type was utilized for the GLM:

$$
\begin{aligned}
Y_i = {} & \mu + \alpha_0 \cdot \mathrm{Asph} + \alpha_1 \cdot \mathrm{Aggr} + \alpha_2 \cdot \%\mathrm{Asph} + \alpha_3 \cdot \mathrm{Voids} \\
& + \alpha_4 \cdot \mathrm{Temp} + \alpha_5 \cdot \mathrm{Stress} + \alpha_6 \cdot \mathrm{Freq} + \alpha_7 \cdot \mathrm{Asph} \cdot \mathrm{Aggr} \\
& + \alpha_8 \cdot \mathrm{Asph} \cdot \%\mathrm{Asph} + \alpha_9 \cdot \mathrm{Asph} \cdot \mathrm{Voids} + \alpha_{10} \cdot \mathrm{Asph} \cdot \mathrm{Temp} \\
& + \alpha_{11} \cdot \mathrm{Asph} \cdot \mathrm{Freq} + \alpha_{12} \cdot \mathrm{Asph} \cdot \mathrm{Stress} + \alpha_{13} \cdot \mathrm{Aggr} \cdot \%\mathrm{Asph} \\
& + \alpha_{14} \cdot \mathrm{Aggr} \cdot \mathrm{Voids} + \alpha_{15} \cdot \mathrm{Aggr} \cdot \mathrm{Temp} + \alpha_{16} \cdot \mathrm{Aggr} \cdot \mathrm{Stress} \\
& + \alpha_{17} \cdot \mathrm{Aggr} \cdot \mathrm{Freq} + \alpha_{18} \cdot \%\mathrm{Asph} \cdot \mathrm{Voids} + \alpha_{19} \cdot \%\mathrm{Asph} \cdot \mathrm{Temp} \\
& + \alpha_{20} \cdot \%\mathrm{Asph} \cdot \mathrm{Stress} + \alpha_{21} \cdot \%\mathrm{Asph} \cdot \mathrm{Freq} \\
& + \alpha_{22} \cdot \mathrm{Voids} \cdot \mathrm{Temp} + \alpha_{23} \cdot \mathrm{Voids} \cdot \mathrm{Stress} + \alpha_{24} \cdot \mathrm{Voids} \cdot \mathrm{Freq} \\
& + \alpha_{25} \cdot \mathrm{Temp} \cdot \mathrm{Stress} + \alpha_{26} \cdot \mathrm{Temp} \cdot \mathrm{Freq} \\
& + \alpha_{27} \cdot \mathrm{Stress} \cdot \mathrm{Freq} \qquad (1)
\end{aligned}
$$

where

Y_1 = response variable, log stiffness,
Y_2 = ratio of diametral stiffness to axial stiffness,
μ = constant (grand mean),
α_i = model coefficients,
Asph = asphalt type,
Aggr = aggregate type,
%Asph = asphalt content,
Voids = percent air voids,
Temp = temperature,
Stress = stress, and
Freq = frequency.

The test method itself (axial or diametral), together with its interactions with other factors, was added to the GLM for modeling the logarithm of resilient stiffness. All independent variables were represented as discrete, binary quantities with the exception of temperature, which was treated as a continuous variable. Summary statistics from this modeling are presented in Table 6. Table 7 identifies by a "Yes" those effects found to be statistically significant at the 95 percent probability level. This means that there is a 5 percent or smaller chance that there actually was no effect in cases for which an effect was observed.

As indicated by the coefficient of determination, the GLM fit closely to the resilient stiffness data. The coefficient of variation of 28.7 percent compares favorably with the 16.7 percent to 36.6 percent range from stiffness measurements taken during the SHRP A-003A compaction study and reported elsewhere (*3*). Although the GLM fit to the ratio data was less accurate, many one-factor and two-factor effects were statistically significant. This means that some of the effects measured by axial test are quite different from the effects measured by diametral test. Such differences could have serious implications for the evaluation of mix effects in a comprehensive AAMAS.

The effects of asphalt type and air-void content on resilient stiffness are illustrated by Figure 1 and Table 8. For the high-temperature testing (Figure 1), there appears to be little distinction between asphalt AAK-1 and AAG-1 based on axial resilient stiffness. At the same time, the ratio of diametral stiffness to axial stiffness is quite different for the two asphalts, varying between 0.75 and 3.25. This variation indicates that the effect of asphalt type on diametral stiffness differs considerably from its effects on axial resilient stiffness. Table 8 confirms that asphalts effect on average axial stiffness at 40°C (104°F) is small and statistically insignificant at the 95 percent level, but its effect on diametral stiffness is much larger and statistically significant. Different results are obtained at lower temperatures as shown in Table 8. At these temperatures it appears that the effect of asphalt type on axial and diametral stiffness is the same, even though the magnitude of the stiffness values is different for the two tests.

One explanation for the differences in the effect of asphalt types on axial and diametral stiffness measurements is that in axial testing at high temperatures, deformations are relatively large and asphalt effects are less important than aggregate effects. At low

TABLE 6 Summary Statistics from GLM Modeling

Statistic	Resilient Stiffness (Ln psi)	Ratio of Diametral Stiffness to Axial Stiffness
Coefficient of Determination (R^2)	0.962	0.587
Root Mean Square Error	0.281	0.281
Coefficient of Variation (%)	28.7	19.4

temperatures, deformations are relatively small and aggregate influence becomes much less pronounced. In diametral testing at high temperatures, on the other hand, stiffness is measured in tension, and larger deformations do not produce more interparticle contact. Therefore, asphalt effects remain more important than aggregate effects.

Mix stiffness is an important feature of the mix analysis and design system. The above illustration underscores the fact that mix-design decisions involving fundamental mix properties might well be influenced by the type of stiffness test.

Effect of Poisson's Ratio

As reported earlier, diametral stiffness values are about 35 to 45 percent higher than corresponding axial stiffness values. Diametral

TABLE 7 Statistically Significant Effects in Stiffness Testing

Effect	Resilient Stiffness	Ratio of Diametral Stiffness to Axial Stiffness
Asphalt Type (Asph)	Yes	
Asphalt Content (%Asph)		Yes
Aggregate Type (Aggr)		
Air Voids (%Voids)	Yes	Yes
Stress Level (Stress)		
Loading Frequency (Freq)		
Temperature (Temp)	Yes	
Type of Test (Test)	Yes	N/A
Asph x % Asph		Yes
Asph x Aggr		
Asph x % Voids		Yes
Asph x Stress		
Asph x Freq		
Asph x Temp	Yes	Yes
Asph x Test	Yes	N/A
% Asph x Aggr		
% Asph x % Voids		
% Asph x Stress		
% Asph x Freq		
% Asph x Temp	Yes	
% Asph x Test		N/A
Aggr x % Voids		Yes
Aggr x Stress		
Aggr x Freq		
Aggr x Temp	Yes	Yes
Aggr x Test	Yes	N/A
% Voids x Stress		Yes
% Voids x Freq		
% Voids x Temp	Yes	Yes
% Voids x Test	Yes	N/A
Stress x Freq		
Stress x Temp	Yes	
Stress x Test		N/A
Freq x Temp		Yes
Freq x Test		N/A
Temp x Test		N/A

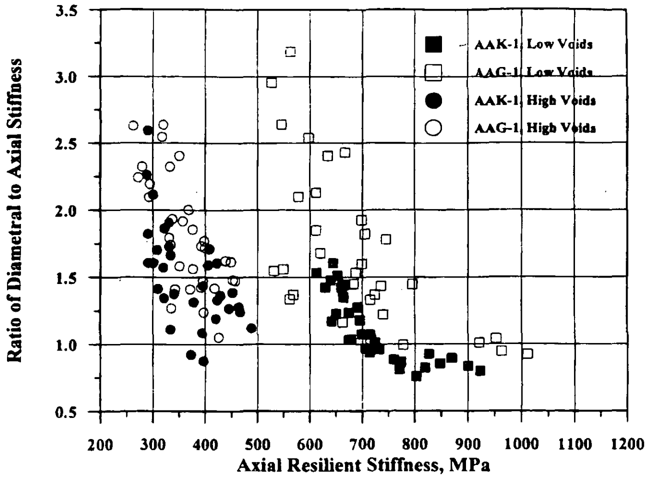

FIGURE 1 Effect of asphalt type and air-void content on resilient stiffness measurements at 40°C.

resilient stiffness values in this study were computed using the following expression *(4–6)*:

$$M_R = \frac{P\,(0.27 + \nu)}{(Ht)} \tag{2}$$

where

P = load,
H = total resilient horizontal deformation,
t = specimen height, and
ν = Poisson's ratio.

Because of difficulty in accurately measuring the resilient vertical deformation from which the Poisson's ratio is calculated, the Poisson's ratio is often assumed to be 0.35. This convention has been adopted for most of the diametral stiffness values reported herein. However, a few computations of diametral stiffness were made using values for Poisson's ratio of 0.1 and 0.2, thought to be representative of behavior at higher loading frequencies and lower temperatures. The diametral stiffness value based on a Poisson's ratio of 0.1 is about 60 percent of the value obtained using a Poisson's ratio of 0.35, as illustrated in Table 9.

Because of the demonstrated sensitivity of diametral resilient stiffness to the assumed value of Poisson's ratio, it was of interest to determine whether axial and diametral results might converge if Poisson's ratios other than 0.35 were used in the computations. Through a trial-and-error process, Poisson's ratios were found for which average axial and diametral stiffnesses were identical. These ratios are summarized in Table 10.

The variation among these ratios is extremely small, and the patterns that were anticipated—lower ratios at cooler temperatures and higher frequencies—were not demonstrated. It is concluded that the observed differences between axial and diametral stiffnesses cannot be logically explained by assumptions about the values of Poisson's ratio.

Poisson's ratio was also a subject of inquiry in the NCHRP investigation *(1)*. When computing Poisson's ratio based on measurements of resilient deformation, both vertical and horizontal, the investigators found extreme variations and concluded that many of the computed ratios were unrealistic and impractical. They attributed this to inappropriateness of linear elastic theory in deriving the expression for the Poisson's ratio. The investigators recommended assuming, not measuring, Poisson's ratio for routine mix design.

In summary, Poisson's ratio cannot be accurately determined from the vertical and horizontal deformations that are measured in indirect tension tests, either because of excessive deformations that may occur in the vicinity of the loading platens and that influence vertical deformation measurements or because of the inappropriateness of linear elastic theory. Moreover, it appears that diametral stiffnesses determined at temperatures below 20°C (68°F) should be

TABLE 8 Illustrative Effect of Test Method on Mix Stiffness

Temperature	Mix	Axial Testing		Diametral Testing	
		Average Resilient Stiffness (MPa)	Statistically Significant Difference?	Average Resilient Stiffness (MPa)	Statistically Significant Difference?
40°C	AAK-1, Low Voids AAG-1, Low Voids	722 691	No	793 1,112	Yes
	AAK-1, High Voids AAG-1, High Voids	368 363	No	542 639	Yes
20°C	AAK-1, Low Voids AAG-1, Low Voids	4,397 7,687	Yes	4,597 10,012	Yes
	AAK-1, High Voids AAG-1, High Voids	2,267 4,759	Yes	3,847 6,997	Yes
0°C	AAK-1, Low Voids AAG-1, Low Voids	14,490 20,948	Yes	18,347 28,083	Yes
	AAK-1, High Voids AAG-1, High Voids	9,287 14,897	Yes	14,062 20,921	Yes

TABLE 9 Example Effect of Poisson's Ratio on Diametral Resilient Stiffness in Megapascals at 0°C Testing Temperature

Test Number	Height, mm	Load, kg	Horizontal Deformation mm	Poisson's Ratio		
				0.10	0.20	0.35
1	66.3	201	0.0013	8,625	10,971	14,490
2	66.3	182	0.0011	8,832	11,178	14,766
3	66.3	388	0.0025	8,487	10,764	14,214
4	66.3	382	0.0024	8,625	10,971	14,490
5	65.0	193	0.0014	7,590	9,591	12,696
6	65.0	172	0.0012	7,797	9,867	13,040
7	65.0	384	0.0029	7,383	9,384	12,350
8	65.0	355	0.0026	7,521	9,591	12,627
Average				8,073	10,281	13,593

computed using values of Poisson's ratio somewhat less than the 0.35 that is normally assumed.

High-Temperature Resilient Stiffnesses

Axial testing was also conducted at 60°C (140°F). During this study, specimens with high air-void contents, especially those containing asphalt AAG-1 and RL aggregate, were observed to undergo excessive plastic (permanent) deformations. Nevertheless, these specimens exhibited relatively larger resilient stiffnesses than ones in which smaller levels of plastic deformation were observed, that is, those specimens containing asphalt AAK-1 and RB aggregate. Table 11 shows the average axial resilient stiffnesses at 60°C (140°F). It may be noted that at this temperature specimens containing AAG-1 asphalt and RB aggregate show lower stiffness values than those containing AAG-1 asphalt and RL aggregate. In addition, the axial stiffness value is higher at higher stress levels than at lower stress levels. It will be noted that higher stress levels result in more plastic (permanent) deformation.

One explanation for these effects is that when a specimen undergoes excessive plastic deformation, the resilient (elastic or recoverable) strain appears to be smaller, because the specimen does not fully recover during the unloading period. Because the resilient stiffness is computed as the ratio of the applied stress to resilient strain, weak specimens (which experience high plastic strain and thus low resilient strain) exhibit apparently higher stiffness values. Figure 2 shows the trace of the axial deformation versus time (number of repetitions) for a relatively weak specimen. It can be seen that the specimen does not fully recover during the unloading phase of the cycle. It will also be noted that the magnitude of the plastic deformation in just 10 cycles is approximately four to five times that of the resilient deformation.

Similar observations were made during diametral testing at 40°C (104°F). At this temperature most of the specimens, especially those with the high air-void content, experienced large plastic deformations at relatively low stress levels (41 to 69 kPa) and at low numbers of repetitions (fewer than 25 to 50). Many of these specimens showed extensive cracking and shear failures (punching) near the loading strips. Due to the extensive distress existing in specimens at this temperature, the diametral testing that had originally been planned for 60°C (140°F) was not performed. It was expected that, at this high temperature, weak specimens (such as those containing high air voids, asphalt AAG-1, and RL aggregate) would fail just from handling, even before testing could be initiated.

Figures 3 and 4 show the vertical and horizontal deformations, respectively, in a diametral test versus time (number of load repetitions) for a relatively weak specimen tested at 40°C (104°F). It should be noted that both plots show extensive accumulation of permanent strain. It should also be noted that in just 11 load repetitions the vertical plastic deformation is about 0.71 mm, whereas the horizontal plastic deformation is about 0.015 mm. The ratio of vertical to horizontal plastic deformation is approximately 50, suggesting extensive localized failure (punching) near the loading strip.

SUMMARY

The comparison of uniaxial compression and indirect tension testing of asphalt-aggregate mixes in this study has revealed the following points:

TABLE 10 Poisson's Ratio for Identical Axial and Diametral Stiffness

Frequency (Hz)	Temperature		
	0°C	20°C	40°C
0.5	0.19	0.16	0.13
1.0	0.18	0.17	0.19

TABLE 11 Effect of Mix and Testing Variables on Average Axial Stiffness at 60°C

Variable	Level	Air Voids	Granite (RB) Average Stress kPa	Granite (RB) Resilient Stiffness MPa	Chert (RL) Average Stress kPa	Chert (RL) Resilient Stiffness MPa
Asphalt Type	AAK-1	Low	46.2	201	48.3	190
		High	44.9	145	37.3	150
	AAG-1	Low	44.9	159	28.3	168
		High	45.5	137	29.7	144
Asphalt Content	Optimum	Low	45.5	184	39.3	176
		High	44.9	150	27.6	140
	High	Low	45.5	176	37.3	182
		High	45.5	132	39.3	155
Stress Level	Low	Low	33.8	169	26.9	173
		High	33.1	127	24.2	138
	High	Low	57.3	190	49.7	185
		High	58.0	155	43.5	157
Frequency	Low	Low	45.5	182	38.0	178
		High	45.5	142	33.8	148
	High	Low	45.5	180	38.6	180
		High	45.5	141	33.1	146
Repeats	First	Low	46.2	176	38.6	190
		High	45.5	132	34.5	157
	Second	Low	44.9	184	38.0	167
		High	45.5	150	32.4	138

1. Both axial and diametral stiffnesses are sensitive to the mix and test variables (asphalt type, aggregate type, air void content and temperature). The low and high stress levels and loading frequencies selected in this study did not significantly affect mix stiffness. The variation of asphalt content in the tested mixes was small; as a result, the observed effects of asphalt content on mix stiffness were relatively small.

2. In general, axial and diametral testing of asphalt-aggregate mixes yield different estimates of their resilient stiffness values. Average diametral resilient stiffness values computed using an assumed Poisson's ratio of 0.35 generally exceed average axial resilient stiffness values by approximately 35 to 45 percent. For individual specimens, diametral resilient stiffness values range from a low of approximately 50 per-

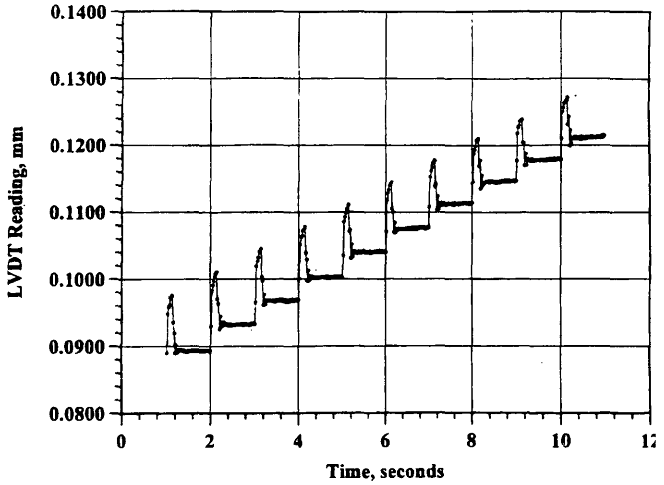

FIGURE 2 Example trace of axial deformation versus time under axial compressive testing.

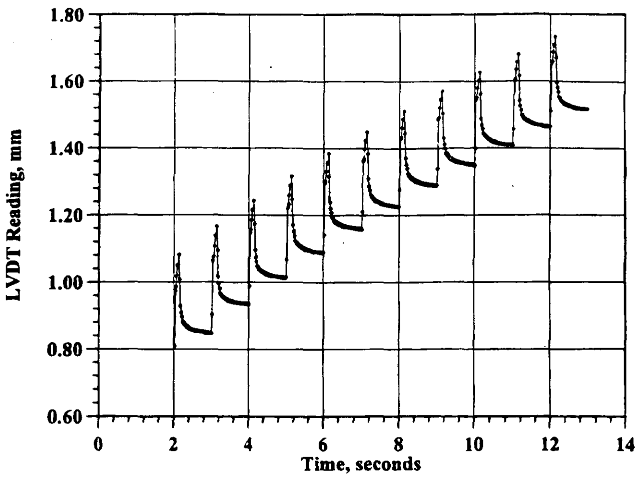

FIGURE 3 Example trace of vertical deformation versus time under diametral testing.

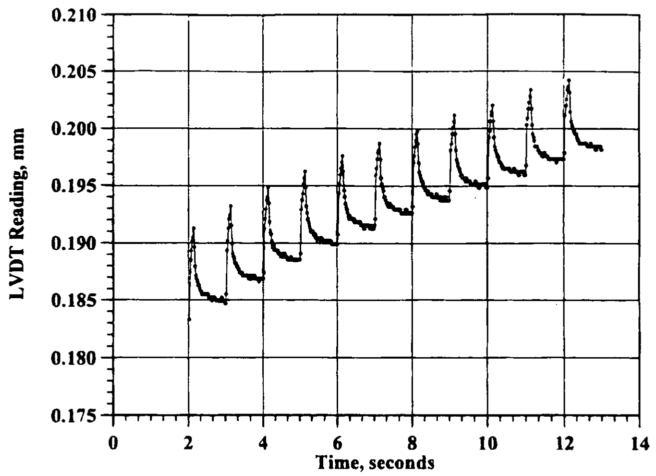

FIGURE 4 Example trace of horizontal deformation versus time under diametral testing.

cent of axial stiffness values to a high of approximately 350 percent.

3. Mix and test effects on resilient stiffness may differ according to whether loading is by axial compression or indirect tension. For example, one asphalt may appear superior if axial testing is employed, while another may appear superior with diametral testing. Such differences in effects on stiffness values arise for various reasons: (*a*) axial test results reflect greater response to shear (aggregate effects), while diametral test results reflect greater response to tension (asphalt effects); and (*b*) under conditions of larger deformations (high temperatures), the larger deformations in the axial test lead to more interparticle contact and, hence, larger stiffness, while larger deformations in the diametral tests may result in less interparticle contact. Such differences could have serious implications for the evaluation of mix effects in a comprehensive asphalt-aggregate mix-design and mix-analysis system.

4. Poisson's ratio, needed to determine resilient stiffness in diametral testing, cannot be accurately determined in the diametral test and must be assumed based on measurements obtained with other test systems. Observed differences between axial and diametral stiffnesses could not be logically explained by assuming the value of Poisson's ratio to be 0.35. Because Poisson's ratio must be assumed, diametral stiffnesses are likely to be less reliable than axial stiffnesses. Diametral stiffness values determined at temperatures below 20°C (68°F) should be computed using values of Poisson's ratio somewhat less than the 0.35 that is normally assumed.

5. Diametral stiffness cannot be accurately measured at high temperatures [60°C (140°F)]. Tests are not reliable even at moderately high temperatures [40°C (104°F)] due to excessive vertical permanent deformation. The SHRP A-003A laboratory experience suggests that weak specimens cannot be tested at temperatures as high as 60°C (140°F). NCHRP investigators also urge caution in "measuring the resilient modulus of elasticity and other properties at higher test temperatures using indirect tensile testing techniques" (*1*). Although they include 60°C (140°F) in their recommended test regime, the large permanent deformations observed in the SHRP A-003A testing cast serious doubt about the reliability of measurements at such temperatures. It seems more effective to limit indirect tension testing for resilient stiffness measurements to temperatures not greatly in excess of 20°C (68°F).

In summary, the indirect tension test appears to be suitable for determining the resilient stiffness of mixes only at low temperatures (and presumably at short loading times as well). At low temperatures, the behavior of asphalt-aggregate mixes is for the most part linearly elastic. ~~However,~~ the stiffness should be measured this way only if Poisson's ratio has been determined with sufficient accuracy from other types of tests.

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