New Relationships Between Structural Properties and Asphalt Mix Parameters

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Improved relationships between some of the fundamental mechanical properties and the mix variables of asphalt are presented and discussed. It is shown that the properties of asphalt mixes can be predicted from a knowledge of several parameters of compacted asphalt mix, magnitude of applied load, and test temperature. During the course of the investigation, a new indirect tensile test apparatus was designed, fabricated, and tested. The apparatus was then used to conduct cyclic load indirect tensile tests using Marshall-type specimens and various asphalt concrete mixes. The indirect tensile test can be used to characterize the elastic, total, creep, permanent deformation, and fatigue behavior of asphalt concrete mixes.

The design of flexible pavement has rapidly evolved from empirical and semiempirical procedures to design methods based on elastic or viscoelastic theories, or both (*1–7*). Today, many highway agencies use such methods in one form or another for the design of new pavements and overlays. This use requires a thorough knowledge of the basic mechanical properties of asphalt paving materials, which are functions of the asphalt mix variables (*8–13*). A variety of tests and test equipment has been developed and employed in laboratories to evaluate these properties (*14–23*). Regardless of the complexity of the tests, test procedures, and test equipment, it was found that different tests yield different results and that test results are difficult to reproduce (*12*). Further, existing asphalt concrete mix design procedures are based on parameters that do not necessarily have any relationship to the structural design of asphalt pavements (*12, 15*).

EXPERIMENTAL PROGRAM

In recognition of the need to tailor asphalt mix design procedures to optimum structural properties and to be able to obtain these parameters from simple tests, a research project sponsored by the FHWA was undertaken at the Department of Civil and Environmental Engineering at Michigan State University (MSU). The objectives of the program included

1. The selection of a simple test and test procedure that will allow the highway engineer to determine the fundamental engineering properties required for the structural design of asphalt pavements.
2. A study of the repeatability of the test results and the number of tests required to reliably obtain the mechanical properties (resilient modulus and Poisson's ratio, fatigue life and permanent deformation characteristics, creep, and viscoelastic properties) of asphalt materials.

Several tests and test procedures were employed. These included triaxial tests (constant and repeated cyclic loads), cyclic flexural tests, Marshall tests, indirect tensile tests (constant and variable cyclic loads), and creep tests. The test data indicated that

1. Repeatability of test results is poor,
2. Material properties obtained from the different tests are substantially different, and
3. Results from the indirect tensile test were the most promising although they were not consistent.

The last observation was made after examining the results of 24 tests (12 tests at a cyclic load of 500 lb and 12 at 100 lb) that were conducted using existing (Schmidt) apparatus. The tests were conducted in triplicate using 100- and 500-lb cyclic loads. The test results are shown in Figure 1. It can be noted that the values obtained for the resilient modulus from a triplicate vary by a factor of 1.9, and those obtained from the 100-lb cyclic load tests are higher than the values from the 500-lb cyclic load tests. Further, during the tests, it was noticed that the measured horizontal deformations were dependent on the placement of the specimen on the lower curved platen (two sequential placements yielded different measurements) and that the upper head of the instrument experienced a slight rocking motion. Hence the inconsistency in the indirect tensile test results appeared to be related to the equipment rather than the test mode. Existing indirect test apparatus have one or more of the following problems:

1. A rocking motion of the loading head, which distorts the accuracy of the vertical deformation of the test specimen.
2. Because of equipment configuration, the test specimen may roll over the lower curved platen resulting in erroneous horizontal deformations.
3. The position of the test specimen on the lower curved platen is arbitrary and differs from one specimen to another.
4. During a repeated load test, the horizontal axis of the test specimen may rotate relative to the vertical axis of the loading head resulting in a smaller measurement of the radial deformation on one side of the diameter than of the opposite side.
5. Lack of capability to measure specimen deformations in three directions indicates that some information available from the test cannot be recorded.

In recognition of these problems, a new indirect tensile test apparatus was designed at MSU and fabricated by the

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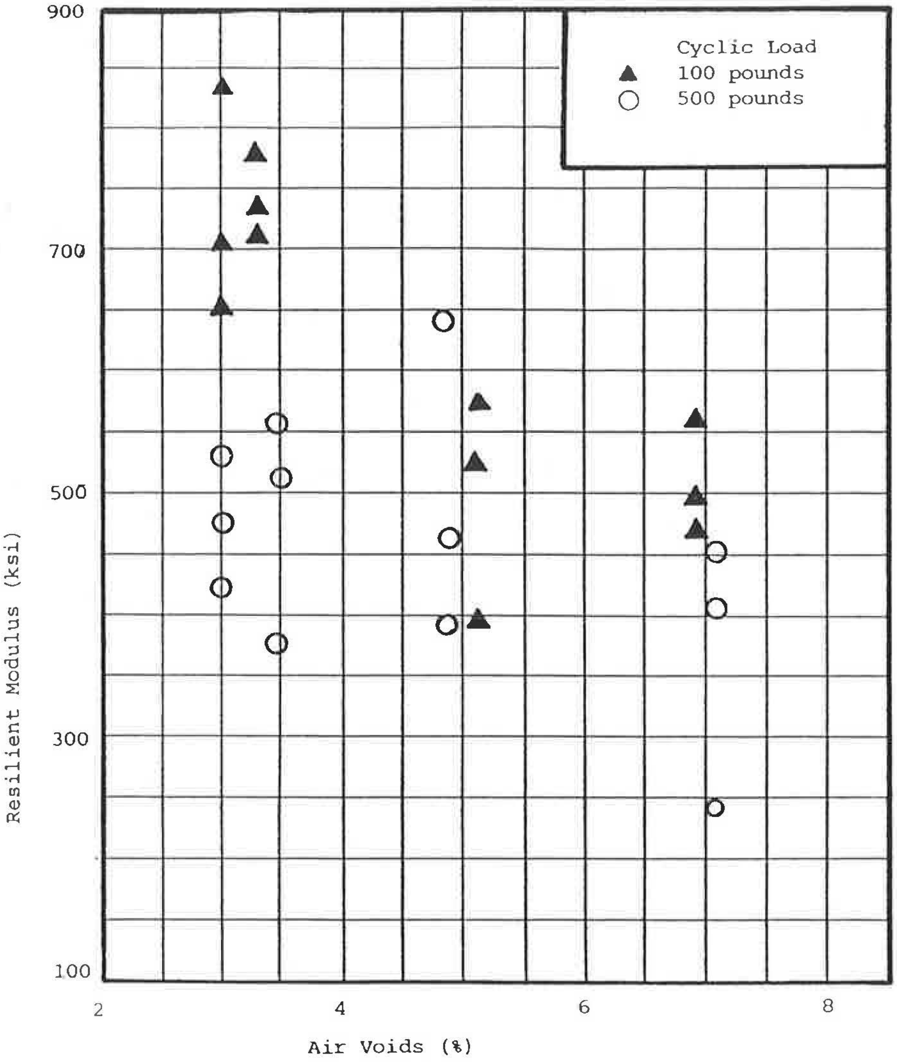

FIGURE 1 Resilient modulus versus percentage of air voids for specimens tested using existing indirect tensile test apparatus.

Michigan Department of Transportation (MDOT). A brief summary of some of the features of that apparatus is presented next.

NEW INDIRECT TENSILE TEST APPARATUS

To overcome the problems associated with existing apparatus, a new simple and inexpensive indirect tensile test apparatus was designed at MSU and later modified and fabricated by personnel of the Division of Testing and Technology at MDOT. The new apparatus possesses the following features:

1. Deformation of the indirect test specimen can be measured in one, two, or three directions using either one or two linear variable differential transducers (LVDTs) in each direction.
2. The apparatus can be used under any existing loading frame (e.g., Marshall, hydraulic system, unconfined, triaxial), and it has a guiding system that consists of four frictionless pistons.
3. The function of the frictionless guiding system is to prevent rotation or rocking, or both, of the upper curved platen of the loading head.
4. The apparatus has four reference positions for easy placement of the apparatus under the center of the loading mechanism of a standard loading frame.
5. The apparatus has a sample stopper for easy positioning of the test specimen on the curved lower platen and for perfect alignment of the horizontal diameter (axis) of the specimen with the axis of the horizontal LVDT or LVDTs.

Complete details of the apparatus along with engineering drawings may be found elsewhere (*24*).

LABORATORY TESTS

The following tests were conducted using the new indirect tensile test apparatus:

1. Indirect tensile tests (INTT) using a standard Marshall loading frame and deformation rate. Some of the test specimens were conditioned as standard Marshall specimens. Others were tested dry at 60°C, 25°C, and 5°C (140°F, 77°F, and 40°F).
2. Indirect constant peak cyclic load (INCCL) tests using an MTS hydraulic system. The specimens were subjected to a

constant sustained load followed by a constant peak cyclic load of 500 lb. Some of the test specimens were subjected to a maximum of 500,000 cycles at a frequency of two cycles per second with a loading time of 0.1 sec and a relaxation period of 0.4 sec. Measurements of the elastic, total, and plastic (permanent) deformations were collected along the vertical and horizontal diameters and the thickness of the specimen. The data were then analyzed to obtain the resilient and total characteristics of the specimens and their fatigue lives.

3. Indirect variable peak cyclic load (INVCL) tests using an MTS hydraulic system. Basically, the test procedure is the same as that of the INCCL test except that, after the application of the sustained load, the specimen was subjected to 100-, 200-, and 500-lb peak cyclic loads each of which was applied for only 1,000 cycles.

A total of 150 specimens were tested in the INTT, 75 in the INCCL test, and 75 in the INVCL test. The results from the last two tests are discussed in this paper.

TEST SPECIMENS

A total of 125 samples (375 specimens) were made and tested using the new indirect test apparatus (75 for each of the INCCL, INVCL, and Marshall tests, and 150 for the INTT). In the remaining parts of this paper, the term "sample" is used to describe one test sample that was later cut to three (triplicate) test specimens. The samples were made using the following materials:

1. Three different types of aggregate (crushed and angular limestone, relatively rounded natural aggregate, and a mix of 50 percent by weight per sieve of the crushed limestone and natural aggregates);
2. Fly ash mineral filler;
3. Two aggregate gradations (Figure 2); and
4. Three viscosity-graded asphalt cements (AC-10, AC-5, and AC-2.5).

For each material combination, a constant percentage of asphalt content was used (the percentage of asphalt content at 3 percent air voids as determined from the standard Marshall mix design). The samples were compacted near three values of percentage air voids (3, 5, and 7 percent) by varying the foot pressure and number of tampings of a kneading compactor. For each material combination and percentage of air void, a cylindrical sample 10.16 cm in diameter and 22 cm high (4 in. by 8.5 in.) was made. Later, the sample was cut into three 6.3-cm-high (2.5-in.) specimens. The three specimens (a triplicate) were then tested under the same conditions (test temperature and test type) using the new indirect tensile test apparatus.

ANALYTICAL MODELS

Several analytical models were developed to calculate the resilient (*25, 26*), total (*27, 28*), plastic (*27, 28*), and fatigue characteristics of the compacted mixes. The resilient and total models are presented in this paper. Other models and analyses are presented elsewhere (*24*). It should be noted that the term "resilient modulus" relates the applied cyclic load to the resilient deformation (immediately recoverable after removing the load). Total modulus, on the other hand, relates applied cyclic load to total deformation.

In the development of the analytical models, it was assumed that the load is applied normal to the contact area between the specimen and the loading strip. This implies that there is no friction between the loading strip and the test specimen (*26*). Assuming plane-stress conditions for homogeneous, isotropic, and linear elastic materials, it can be shown that the resilient

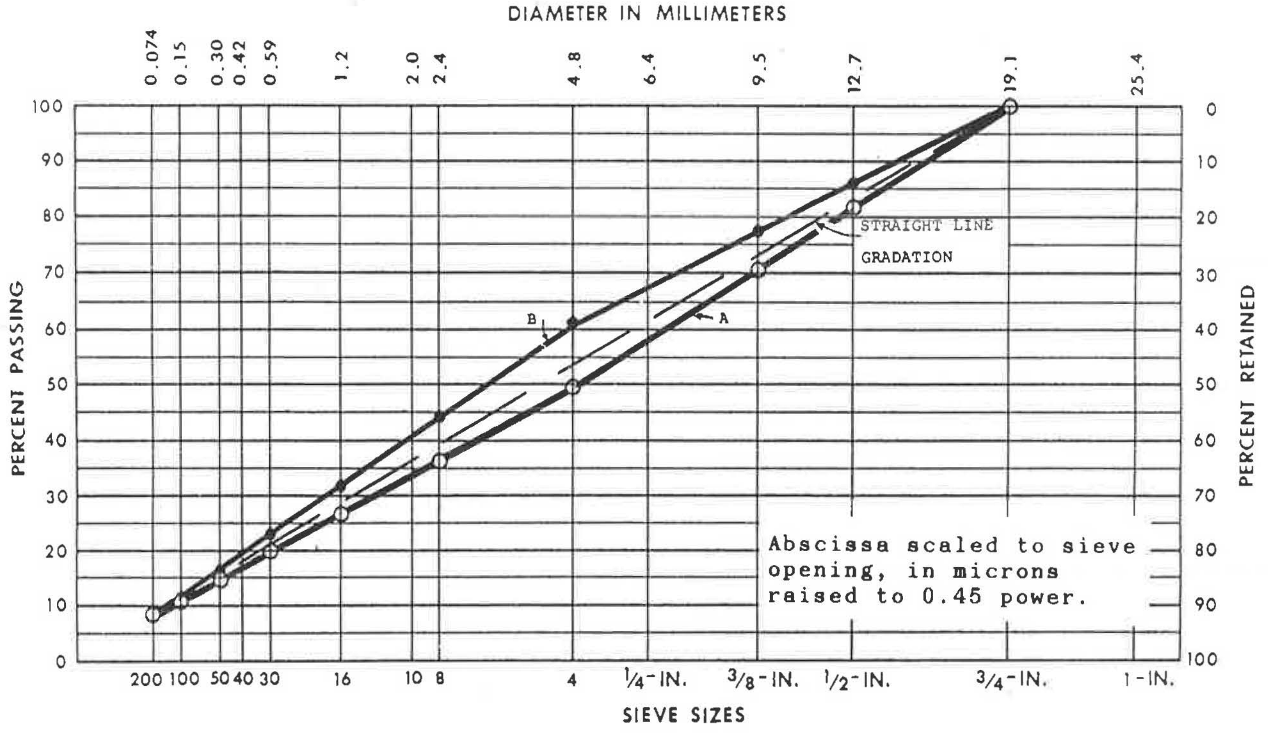

FIGURE 2 Gradations A and B for all three aggregates and the straight line gradation.

and total moduli and Poisson's ratios are given by the following equations:

$$U = \frac{3.58791 - 0.269895\,(DR)}{0.062745 + DR} \tag{1}$$

$$M_R \text{ or } E = \frac{P\,[3.58791 - 0.062745\,(U)]}{L(DV)} \tag{2}$$

$$M_R \text{ or } E = \frac{0.319145\,(P)\,(U)}{DL} \tag{3}$$

$$INCS = \frac{0.475386\,(P)}{L} \tag{4}$$

$$INTS = \frac{0.156241\,(P)}{L} \tag{5}$$

where the constants in the equations result from integration, and

U = Poisson's ratio,
DR = deformation ratio = DV/DH,
DV = vertical resilient or total deformation of the specimen along the vertical diameter (in.),
DH = horizontal resilient or total deformation of the specimen along the horizontal diameter (in.),
DL = radial deformation along the longitudinal axis (thickness) of the specimen (in.),
M_R = resilient modulus (psi),
E = total modulus (psi),
L = sample thickness (in.),
P = magnitude of the applied load (lb),
$INCS$ = indirect compressive strength at the center of the test specimen (psi), and
$INTS$ = indirect tensile strength at the center of the test specimen (psi).

Theoretically, the values of the resilient modulus from Equations 2 and 3 should be exactly the same for homogeneous, isotropic, and linear elastic material. Asphalt mixes are heterogeneous and anisotropic. As a result of this and measurement errors, differences between the two calculated values should be expected. Equation 2 can be used if the radial deformation (DL) is not measured. If the sample deformations in all three directions are measured, the two values of the calculated resilient modulus from Equations 2 and 3 should be compatible (a maximum difference of 5 percent was observed in this study). Substantial difference between these two values may mean that the test results are not accurate. A better procedure is to estimate the modulus and Poisson's ratio using all measurements. The following equations were developed using least square techniques and Equations 1–3:

$$\begin{aligned} U = {} & [0.225127(H^2) - 0.269895(V^2) - 0.0447676(A^2) \\ & + 3.570975(H)(V) + 0.086136(A)(H) \\ & + 1.145064(A)(V)]/\mathrm{D} \end{aligned} \tag{6}$$

$$\begin{aligned} M_R \text{ or } E = {} & [0.253680(H) + 3.9702876(V) \\ & - 0.0142874(A)]/D \end{aligned} \tag{7}$$

where

D = $1.105791\,(H^2 + V^2 + A^2) - [H - 0.0627461(V) + 0.319145(A)]^2$;
H = $DH(L/P)$;
V = $DV(L/P)$;
A = DL/P; and
M_R, E, DH, DV, DL, L, and P are as before.

If the sample deformations are measured in all three directions, Equations 6 and 7 yield the best estimates of the resilient modulus and Poisson's ratio. However, if one of these three deformations is not available, Equations 1 and 2 or 3 should be used.

STATISTICAL MODEL

Recall that 125 samples were compacted and 375 specimens were made. Seventy-five specimens were tested using the INCCL test and another 75 using the INVCL test. For each test specimen, the resilient and total moduli and Poisson's ratios were then calculated by using Equations 1–7. It was found that

1. The maximum difference between values of the moduli obtained from Equations 2 and 3 was less than 5 percent;
2. Equations 6 and 7 yielded more consistent results than did Equations 1–3; and
3. The maximum difference in the values of the moduli (elastic and total) obtained from a triplicate was less than 7 percent.

Nevertheless, the values calculated from Equations 6 and 7 were statistically correlated with the test and specimen variables using the stepwise procedure of a multivariate linear regression program SPSS/PC+ (*29*). In this procedure, the most highly correlated variable (to the test results) was analyzed first (all other variables were not included); the second most significant was then added, and so forth; the least significant was the last variable included in the analysis. At each step, an equation relating the test results and the variable or variables was produced along with the coefficients of correlation and standard error and a partial correlation matrix (PCM). Variables that did not have a significance level higher than 0.05 percent relative to the previous variable were automatically excluded from the final equation. The advantages of this method follow:

1. At each step, the variables in the equation are listed in order of significance;
2. The interaction between variables can be qualitatively assessed by comparing the regression coefficients from two consecutive steps and by examining the values of the partial correlation coefficient listed in the PCM; and
3. The method produces the simplest and most efficient possible equation.

The specimen and test variables for all tests are

1. Air voids (AV) of the test specimens,
2. Kinematic viscosity (KV) of the asphalt binder,
3. Gradation ($GRAD$) of the aggregates,
4. Aggregate angularity (ANG),

5. Magnitude of cyclic load (*CL*),
6. Number of load repetitions (*N*), and
7. Test temperature (*TT*).

During the analysis, for each independent variable, several transformations (arithmetic, exponential, and logarithmic) relating the dependent and independent variable were also explored. The final form was selected on the basis of its simplicity, physical interpretation, and the values of the coefficients of correlation and standard error.

Table 1 gives a summary of the regression matrix (regression coefficients, coefficients of correlation, and the standard error of the resulting equation from each step of the analysis) of the resilient modulus. It can be noted that

1. The most significant variable affecting the resilient modulus is *TT*.
2. The value of the regression coefficient of *TT* is only slightly affected as more variables are included in the analysis. This observation implies that *TT* is independent and there is little or no interaction between this variable and the others.
3. Apparently there is some interaction between plastic deformation (*CD*1) and percentage of air voids (*AV*), and between *CD*1 and the magnitude of the cyclic load (*ACL*). This was expected because as plastic deformation increases, the air voids either decrease (densification) or increase (dilatation). Similarly, as plastic deformation increases, response of the specimen to the cyclic load will change.
4. The values of the coefficient of correlation and standard error have indicated consistency in the test results. This could be related to the extra care exercised during the tests and to the features of the new apparatus.

Equation 8 is the final regression equation relating the resilient modulus to the specimen and mix variables.

$$\begin{aligned}\ln(M_R) &= 16.097 - 0.03634(TT) - 0.1349(AV)\\ &\quad - 0.0002653(CL) + 0.04586(ANG)\\ &\quad + 0.0009142(KV) - 0.00004688(CD1)\\ &\quad - 0.02456(GRAD) - 0.005924[\ln(N)]\\ R^2 &= 0.999;\ SE = 0.017\end{aligned} \qquad (8)$$

TABLE 1 REGRESSION MATRIX FOR RESILIENT MODULUS OF COMPACTED ASPHALT MIXES USING CONSTANT AND VARIABLE PEAK CYCLIC LOADS

DEPENDENT VARIABLE RESILIENT MODULUS (M_R)	INTERCEPT	REGRESSION COEFFICIENT OF THE INDEPENDENT VARIABLE								R^2	S.E.
		TT (10^{-2})	AV (10^{-1})	ACL (10^{-4})	AG (10^{-2})	KV (10^{-4})	CD1 (10^{-5})	GR (10^{-2})	lnN (10^{-3})		
$\ln(M_R)$	15.724	-3.778	-	-	-	-	-	-	-	0.885	0.2190
	16.266	-3.578	-1.403	-	-	-	-	-	-	0.983	0.085
	16.401	-3.582	-1.428	-3.398	-	-	-	-	-	0.991	0.061
	16.291	-3.628	-1.393	-3.397	3.969	-	-	-	-	0.994	0.049
	16.092	-3.658	-1.401	-3.409	4.353	8.793	-	-	-	0.997	0.033
	16.029	-3.601	-1.363	-2.684	4.441	8.625	-5.829	-	-	0.999	0.022
	16.043	-3.617	-1.334	-2.663	4.644	9.125	-5.909	-2.547	-	0.999	0.019
	16.097	-3.634	-1.349	-2.653	4.586	9.142	-4.688	-2.456	-5.924	0.999	0.017

ln = natural log;
TT = test temperature;
AV = air voids;
ACL = actual cyclic load;
AG = angularity;
KV = kinematic viscosity;
CD1 = plastic deformation along the vertical diameter (inches);
GR = gradation;
N = number of applications;
R^2 = coefficient of correlation;
S.E. = standard error; and
\- = not applicable.

where

ln = natural logarithm;
M_R = resilient modulus (psi);
TT = test temperature (°F);
AV = percentage of air voids (AV = 1, 2, 3, etc.);
CL = applied cyclic load (lb);
L = actual sample thickness (in.);
ANG = aggregate angularity (angularity was assigned a scale of from 1 to 4; a value of 1 represents perfectly spherical and smooth particles, and 4 represents highly angular particles); for this study the angularity of the crushed limestone is 4, that of the rounded natural aggregate is 2, and the angularity of the 50 percent by weight mix was given a value of 3;
KV = kinematic viscosity of the asphalt at 135°C (275°F) (cSt) (AASHTO T201);
$CD1$ = cumulative vertical plastic deformation (in.);
$GRAD$ = gradation factor ($GRAD$ = 1 for Gradation A and 0.98 for Gradation B); because only two gradations were used in this project, a meaningful relationship between $GRAD$ and the resilient modulus cannot be obtained;
N = the number of load repetitions;
R^2 = coefficient of correlation; and
SE = standard error.

From a practical viewpoint, Equation 8 can be simplified by considering only five variables: TT, AV, CL, ANG, and KV. This is because the additional variables add little to the explanatory power, in a statistical sense, and their net impact on the actual predicted values of $\ln(M_R)$ is minimal. Therefore the equation reduces to (the fifth step of the stepwise procedure)

$$\begin{aligned}\ln(M_R) = {} & 16.092 - 0.03658(TT) - 0.1401(AV) \\ & - 0.0003409(CL) + 0.04353(ANG) \\ & + 0.0008793(KV) \\ R^2 = {} & 0.997;\ SE = 0.033 \end{aligned} \tag{9}$$

where all variables are as before.

The sensitivity of the values of the resilient modulus predicted by Equation 9 to variations in the values of the independent variables (TT from 40°F to 77°F; AV from 3 to 7 percent; CL from 100 to 500 lb, ANG from 2 to 4, and KV from 159 to 270 cSt) was studied. It was noted that

1. The values of the resilient modulus increase by a factor of 3.76 as the temperature decreases from 77°F to 40°F;
2. A decrease in the percentage of air voids from 7 to 3 percent results in an increase in the resilient modulus by a factor of 1.76;
3. An increase in the applied load from 100 to 500 lb results in a reduction in the modulus by a factor of 1.15;
4. The values of the resilient modulus increase by a factor of 1.09 as ANG increases from 2 (rounded aggregate) to 4 (crushed aggregate); and
5. Increasing KV from 159 to 270 cSt leads to increasing M_R by a factor of 1.1.

These observations imply that the asphalt mix has a nonlinear elastic behavior (greater load yields lower modulus values). The significance of this is that existing standard test procedures (e.g., ASTM D4123) specify that the resilient modulus tests be conducted using low magnitudes of the cyclic load. This will result in higher estimates of the resilient modulus than would be the case at greater loads. A correct evaluation of the values of the total or resilient modulus should include the sensitivity of these values to the range of load anticipated in the field (i.e., obtain the relationship between M_R or E and CL). Further, it is stated in ASTM D4123 that "if Poisson's ratio is assumed, the vertical deformations are not required. A value of 0.35 for Poisson's ratio has been found to be reasonable for asphalt mixtures at 77°F." The values of the resilient modulus in this study were also calculated (as specified by ASTM D4123) using the measured horizontal deformation and an assumed value of Poisson's ratio of 0.35. It can be seen that the assumption of Poisson's ratio of 0.35 consistently yields higher modulus values. An assumed Poisson's ratio of 0.27 yields better estimates of the values of M_R for most data points. It should be noted that a change in the assumed value of Poisson's ratio of 0.01 results in a change of approximately 2 percent in the value of M_R. Because Poisson's ratio of asphalt mixes is a function of the mix and test variables (see Equation 12), it is strongly recommended that Poisson's ratio be calculated using measured vertical and horizontal deformations.

Nevertheless, Figure 4 shows the measured and calculated resilient modulus using Equation 9. The straight line in the figure represents equality between measured and calculated values. It should be noted that the maximum difference between the arithmetic (not logarithmic) values of the measured and calculated data (using Equation 9) is 8 percent. This difference is only 3 percent for Equation 8.

A regression matrix for the total modulus (E) was obtained. It was noted that the order of the variables in this matrix was the same as that for the resilient modulus (Table 1). Comparison of the values of the regression coefficients from the two matrices indicates that the test temperature and the percentage of air voids have slightly greater effects on the total modulus than on the resilient modulus. This was expected because the total modulus reflects elastic and viscoelastic behavior whereas the resilient modulus reflects only elastic behavior. This implies that higher temperatures increase the viscoelastic component of the deflection (strain) more than they increase the resilient component. Nevertheless, Equation 10 expresses E in terms of the sample and test variables.

$$\begin{aligned}\ln(E) = {} & 16.385 - 0.04529(TT) - 0.1549(AV) \\ & - 0.0003339(CL) + 0.04258(ANG) \\ & + 0.0008364(KV) \\ R^2 = {} & 0.998;\ SE = 0.034 \end{aligned} \tag{10}$$

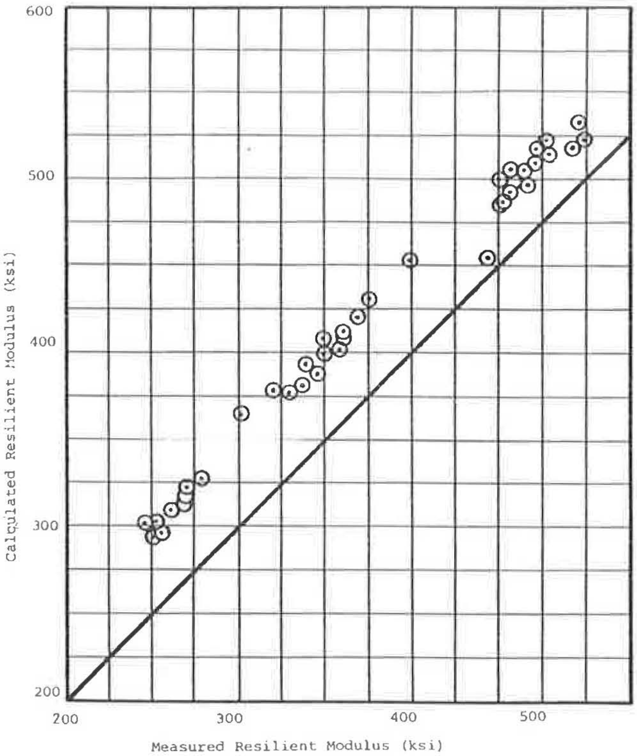

FIGURE 3 Calculated versus measured resilient modulus using the ASTM D4123 standard test procedure.

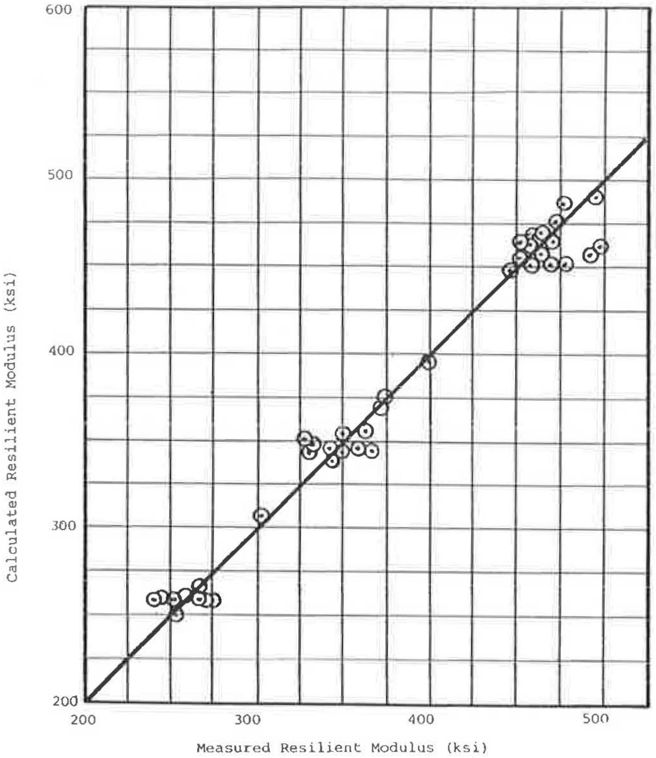

FIGURE 4 Calculated versus measured resilient modulus.

A plot of the measured versus calculated values of E (using Equation 10) showed a trend similar to that of the resilient one.

The regression matrices for the resilient and total Poisson's ratio are given in Tables 2 and 3, respectively. It should be noted that

1. The order of significance of the variables in the matrices is different; TT is the most significant factor affecting the total Poisson's ratio, but it is fourth for the resilient Poisson's ratio, and
2. The value of the coefficient of correlation for the resilient Poisson's ratio is quite low (0.275).

The first observation was expected because the values of the total Poisson's ratio reflect both elastic and viscoelastic behavior; viscoelastic behavior is more temperature sensitive than is elastic. The second observation does not mean that the values of the resilient Poisson's ratio are inconsistent. It should be recalled that the variable peak cyclic load tests were conducted using 100-, 200-, and 500-lb cyclic loads. The horizontal resilient deformations for the 100-lb cyclic load (at 400°F) were on the same order of magnitude as the accuracy of the measurement system (0.00001 in.). Hence these measurements are not reliable for analytical purposes. Total deformations, on the other hand, were higher and consequently the values of the total Poisson's ratio are more consistent. When the data for the 100-lb cyclic load were excluded, the regression matrix of Table 4 was obtained. Note that the order of the variables in this matrix is different from that in Table 2. Also, values of the regression coefficients and the coefficients of correlation and standard error are considerably different.

These comments support the statement made concerning the ASTM D4123 standard: conducting the INCCL tests using a low value of cyclic load will yield inconsistent and misleading results unless the accuracy of measurement is improved.

Using the results given in Tables 3 and 4, and neglecting the last two variables in both tables because they have negligible impact on the values of ln(PT) and ln(PR), Equations 11 and 12 can be obtained for the total and resilient Poisson's ratios, respectively.

$$\ln(PT) = -0.43228 - 0.01940(TT) - 0.06329(AV) + 0.001332(KV) + 0.0001236(CL)$$
$$R^2 = 0.913;\ SE = 0.108 \qquad (11)$$

$$\ln(PR) = -1.370 - 0.04243(AV) + 0.000885(KV) + 0.004662[\ln(N)] + 0.0004489(TT)$$
$$R^2 = 0.720;\ SE = 0.045 \qquad (12)$$

It can be noted that although the resilient Poisson's ratio is dependent on the number of load repetitions (N), the total Poisson's ratio is independent. The reason for this is that increasing N yields higher resilient deformation and lower viscoelastic deformation. Hence total deformation is more or less independent of N. Figure 5 shows the measured and calculated resilient Poisson's ratio using Equation 12. The line representing the value of Poisson's ratio of 0.35 is also shown. It is clear that assuming a Poisson's ratio value of 0.35 for all mixes is not appropriate. Therefore it is strongly recommended that values of Poisson's ratio be calculated using measured horizontal and vertical deformations. A similar plot can be obtained for total Poisson's ratio.

TABLE 2 REGRESSION MATRIX FOR RESILIENT POISSON'S RATIO OF COMPACTED ASPHALT MIXES USING CONSTANT AND VARIABLE PEAK CYCLIC LOADS

DEPENDENT VARIABLE RESILIENT POISSON'S RATIO (PR)	INTERCEPT	REGRESSION COEFFICIENT OF THE INDEPENDENT VARIABLE						R^2	S.E.
		AV (10^{-2})	KV (10^{-3})	ACL (10^{-4})	TT (10^{-3})	CD1 (10^{-5})	lnN (10^{-2})		
ln(PR)	-1.179	-3.088	-	-	-	-	-	0.076	0.156
	-1.428	-3.280	1.075	-	-	-	-	0.153	0.150
	-1.511	-3.117	1.071	2.150	-	-	-	0.208	0.145
	-1.623	-3.485	0.979	2.170	2.231	-	-	0.254	0.141
	-1.654	-3.297	0.969	2.539	2.529	-2.972	-	0.260	0.140
	-1.793	-2.929	0.957	2.510	3.028	-6.182	1.566	0.275	0.139

ln = natural log;
TT = test temperature;
AV = air voids;
ACL = actual cyclic load;
KV = kinematic viscosity;
CD1 = plastic deformation along the vertical diameter (inches);
N = number of applications;
R^2 = coefficient of correlation;
S.E. = standard error; and
\- = not applicable.

TABLE 3 REGRESSION MATRIX FOR TOTAL POISSON'S RATIO OF COMPACTED ASPHALT MIXES USING CONSTANT AND VARIABLE PEAK CYCLIC LOADS

DEPENDENT VARIABLE TOTAL POISSON'S RATIO (PT)	INTERCEPT (10^{-2})	REGRESSION COEFFICIENT OF THE INDEPENDENT VARIABLE						R^2	S.E.
		TT (10^{-2})	AV (10^{-2})	KV (10^{-3})	ACL (10^{-4})	ANG (10^{-2})	GRAD (10^{-2})		
ln(PT)	-34.333	-1.986	-	-	-	-	-	0.829	0.151
	-38.948	-1.915	-6.218	-	-	-	-	0.887	0.123
	-38.554	-1.937	-6.433	1.328	-	-	-	0.910	0.110
	-43.228	-1.940	-6.329	1.332	1.236	-	-	0.913	0.108
	-37.314	-1.915	-6.501	1.295	1.241	-1.905	-	0.915	0.106
	-39.370	-1.887	-6.916	1.211	1.236	-2.197	3.618	0.917	0.105

ln = natural log;
TT = test temperature;
AV = air voids;
ACL = actual cyclic load;
KV = kinematic viscosity;
ANG = aggregate angularity;
grad = aggregate gradation;
R^2 = coefficient of correlation;
S.E. = standard error; and
\- = not applicable

TABLE 4 REGRESSION MATRIX FOR RESILIENT POISSON'S RATIO OF COMPACTED ASPHALT MIXES USING CONSTANT AND VARIABLE PEAK CYCLIC LOADS (100-lb load excluded)

DEPENDENT VARIABLE RESILIENT POISSON'S RATIO (PR)	INTERCEPT	REGRESSION COEFFICIENT OF THE INDEPENDENT VARIABLE						R^2	S.E.
		AV (10^{-2})	KV (10^{-4})	lnN (10^{-3})	TT (10^{-4})	ACL (10^{-4})	CD1 (10^{-6})		
ln(PR)	-1.101	-4.109	-	-	-	-	-	0.503	0.059
	-1.310	-4.269	9.003	-	-	-	-	0.705	0.046
	-1.343	-4.186	9.035	4.030	-	-	-	0.713	0.045
	-1.370	-4.243	8.850	4.662	4.489	-	-	0.720	0.045
	-1.765	-4.281	8.901	4.471	4.181	7.954	-	0.722	0.045
	-1.797	-4.168	8.856	6.219	5.948	8.117	-9.146	0.724	0.044

ln = natural log;
TT = test temperature;
AV = air voids;
ACL = actual cyclic load;
KV = kinematic viscosity;
CD1 = plastic deformation along the vertical diameter (inches);
N = number of applications;
R^2 = coefficient of correlation;
S.E. = standard error; and
\- = not applicable.

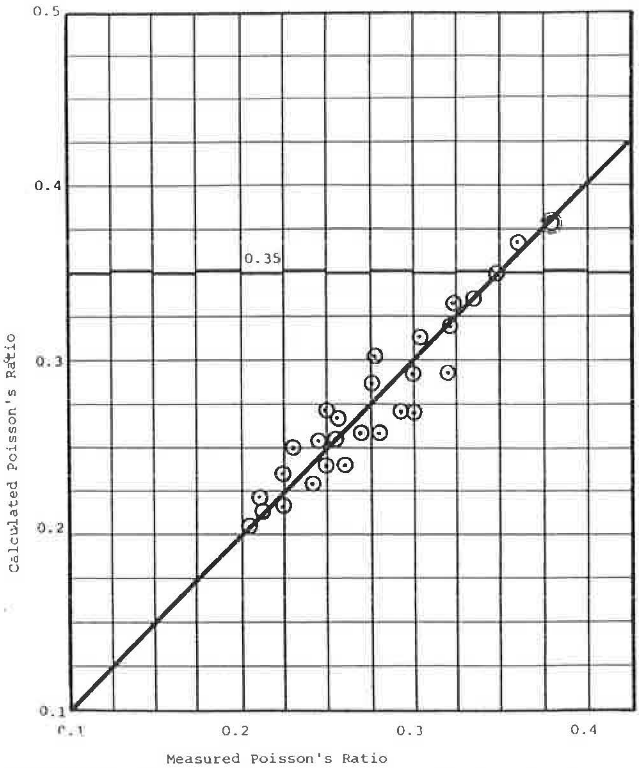

FIGURE 5 Calculated versus measured Poisson's ratios.

CONCLUSIONS

On the basis of test results and analytical and statistical analyses, the following conclusions were drawn:

1. The resilient characteristics of asphalt mixes can be expressed in terms of the mix and test variables.
2. The test temperature and the percentage of air voids in the mix have the greatest influence on the resilient characteristics of the mix.
3. The resilient modulus decreases as the number of load repetitions increases (softening effects).
4. Poisson's ratio of the mixes is dependent on the air voids in the mix and the kinematic viscosity of the binder.
5. Increasing aggregate angularity causes an increase in the resilient modulus.
6. Higher asphalt binder viscosity produces stiffer mix and higher resilient characteristics.
7. For any test specimen, the test results are consistent and quite reasonable.
8. The maximum difference in the values of the resilient or total moduli obtained from a triplicate is only 7 percent.
9. The values of Poisson's ratio for all 414 specimens vary from 0.23 to 0.32. Further, for any triplicate, Poisson's ratio is almost constant.
10. For any combination of variables, the test results can be accurately reproduced.

11. The ASTM standard test procedure D-4123 is inadequate and may lead to misleading results.

SUMMARY

A knowledge of the fundamental mechanical properties of flexible pavement materials is essential for the structural design of pavements. This basic knowledge becomes increasingly important as more highway engineers use pavement design systems based on elastic or viscoelastic theories, or both, that require estimates of these properties. Further, a proper asphalt concrete mix design procedure should be based on these fundamental properties. A new indirect tensile test apparatus was designed and used in this study to calculate asphalt mix properties. The test is simple and yields consistent results. Values of calculated resilient and total characteristics were compatible with those measured during actual tests.

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REFERENCES

1. *Interim Guide for Design of Pavement Structures.* AASHTO, Washington, D.C., 1972, Chapter III, revised 1981.
2. G. Y. Baladi. Characterization of Flexible Pavement: A Case Study. Special Technical Paper 807. ASTM, Philadelphia, Pa., 1983.
3. W. J. Kenis. Material Characterizations for Rational Pavement Design. Special Technical Paper 561. ASTM, Philadelphia, Pa., 1973.
4. J. S. Miller, J. Uzan, and M. W. Witczak. Modification of the Asphalt Institute Bituminous Mix Modulus Predictive Equation. In *Transportation Research Record 911*, TRB, National Research Council, Washington, D.C., 1983, pp. 27–36.
5. L. W. Nijboer. Mechanical Properties of Asphalt Materials and Structural Design of Asphalt Roads. *HRB Proc.*, Vol. 33, HRB, National Research Council, Washington, D.C., 1954, pp. 185–200.
6. J. F. Shook and B. F. Kallas. Factors Influencing Dynamic Modulus of Asphalt Concrete. *Proc.*, Association of Asphalt Paving Technologists, Vol. 38, 1969, pp. 140–178.
7. E. J. Yoder and M. W. Witczak. *Principles of Pavement Design*, 2nd ed. John Wiley and Sons Inc., New York, 1975.
8. *Asphalt Overlays for Highway and Street Rehabilitation.* Manual Series 17. The Asphalt Institute, College Park, Md., June 1983.
9. S. F. Brown and K. E. Cooper. A Fundamental Study of the Stress-Strain Characteristics of a Bituminous Material. *Proc.*, Association of Asphalt Paving Technologists, Vol. 49, 1980, pp. 476–499.
10. F. N. Finn. *NCHRP Report 39: Factors Involved in the Design of Asphaltic Pavement Surfaces.* TRB, National Research Council, Washington, D.C., 1967.
11. B. F. Kallas and J. F. Shook. Factors Influencing Dynamic Modulus of Asphalt Concrete. *Proc.*, Association of Asphalt Paving Technologists, Vol. 38, 1969.
12. H. L. Von Quintus, J. B. Rauhut, and T. W. Kennedy. Comparisons of Asphalt Concrete Stiffness as Measured by Various Testing Techniques. *Proc.*, Association of Asphalt Paving Technologists, Vol. 51, 1982, pp. 35–52.
13. M. W. Witczak and R. E. Root. Summary of Complex Modulus Laboratory Test Procedures and Results. Special Technical Paper 561. ASTM, Philadelphia, Pa., 1974.
14. *AASHTO Test and Materials Specifications*, 13th ed. AASHTO, Washington, D.C., 1982, Parts 1 and 2.
15. *Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types.* Manual Series 2. The Asphalt Institute, College Park, Md., 1979.
16. M. H. Farzin, R. J. Krizek, and R. B. Corotis. Evaluation of Modulus and Poisson's Ratio from Triaxial Tests. In *Transportation Research Record 537*, TRB, National Research Council, Washington, D.C., 1975, pp. 69–80.
17. W. H. Goetz. Comparison of Triaxial and Marshall Test Results. *Proc.*, Association of Asphalt Paving Technologists, Vol. 20, 1951, pp. 200–245.
18. G. Gonzalez, T. W. Kennedy, and J. N. Anagnos. *Evaluation of the Resilient Elastic Characteristics of Asphalt Mixtures Using the Indirect Tensile Test.* Report CFHR 3-9-72-183-6. Transportation Planning Division, Texas State Department of Highways and Public Transportation, Austin, Nov. 1975.
19. W. O. Hadley and H. Vahida. A Fundamental Comparison of the Flexural and Indirect Tensile Tests. In *Transportation Research Record 911*, TRB, National Research Council, Washington, D.C., 1983, pp. 42–51.
20. J. F. Hills and W. Heukelom. The Modulus and Poisson's Ratio of Asphalt Mixes. *Journal of the Institute of Petroleum*, Vol. 55, Jan. 1969, pp. 27–35.
21. T. W. Kennedy. Characterization of Asphalt Pavement Materials Using the Indirect Tensile Test. *Proc.*, Association of Asphalt Paving Technologists, Vol. 46, 1977, pp. 132–150.
22. C. L. Monismith. Flexibility Characteristics of Asphalt Paving Mixtures. *Proc.*, Association of Asphalt Paving Technologists, Vol. 27, 1958, pp. 74–106.
23. P. S. Pell and S. F. Brown. The Characteristics of Materials for the Design of Flexible Pavement Structures. *Proc.*, 3rd International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, Vol. I, 1972, pp. 326–342.
24. G. Y. Baladi. *Integrated Material and Structural Design Method for Flexible Pavements.* Final Report FHWA/RD-88/109, 110, and 118. FHWA, U.S. Department of Transportation, Sept. 1987.
25. S. P. Timoshenko and J. N. Goodier. *Theory of Elasticity.* McGraw Hill Book Company, New York, 1970.
26. M. A. Young and G. Y Baladi. *Repeated Load Triaxial Testing, State of the Art.* Division of Engineering Research, Michigan State University, East Lansing, 1977.
27. G. Y. Baladi. *Linear Viscosity.* U.S. Army Engineers Waterways Experiment Station, Vicksburg, Miss., Oct. 1985.
28. G.. Baladi. *Numerical Implementation of a Transverse-Isotropic, Inelastic, Work-Hardening Constitutive Model.* Soil Dynamics Division, Soils and Pavement Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Oct. 1985.
29. M. Norusis. *SPSS/PC+ for the IBM PC/XT/AT.* SPSS Inc., Chicago, Ill., 1986.

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