EVALUATION AND PREDICTION OF THE TENSILE PROPERTIES OF ASPHALT-TREATED MATERIALS

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The increased use of asphalt-stabilized subbases in rigid pavement structures has created the need for a rational procedure by which to design these subbases. A design procedure based on layered theory is presently under development at the University of Texas at Austin to satisfy this need. This theoretical design method consequently requires that material characterization constants such as modulus of elasticity, Poisson's ratio, and failure strains be estimated for a variety of asphalt-stabilized materials. This paper describes a study that was undertaken to evaluate the effects of 7 different factors on the tensile properties of asphalt-treated materials. The 7 factors investigated include aggregate type, aggregate gradation, asphalt viscosity, asphalt content, mixing temperature, compaction temperature, and curing temperature. The test responses discussed are modulus of elasticity, tensile strength, and total tensile strain. The results reported were obtained from a carefully controlled indirect tensile test. The data from this study indicate that there is no trend or correlation between either modulus of elasticity and density or tensile strength and density. Hence, changes in density alone cannot be used as a measure of changes in tensile properties of asphalt-treated materials but must be accompanied by careful consideration of the factors involved in the mix design. Because of the dominant effect of compaction temperature on the 3 tensile properties, it is recommended that present laboratory test procedures be extended to include the evaluation of the effect of changes in compaction temperature and that closer control of compaction temperature in the field be established through specification requirements.

•THE INCREASED use of asphalt-stabilized materials as subbases for rigid pavements has created the need for a rational design procedure for these highway materials. To satisfy this need, a design procedure based on layered theory is presently under development at the University of Texas at Austin (1). Such a procedure requires that material characterization constants such as modulus of elasticity, Poisson's ratio, and failure strain be known for a variety of highway materials. Estimated values of these tensile properties can be obtained from indirect tensile test results (2, 3, 4).

In previous work (2) the tensile strengths for asphalt-treated materials involving a wide variety of mix variables were evaluated. This previous screening study provided insight into the complexity of the asphalt-stabilization process and indicated that interactions of 2 or more variables are involved. The study, however, had 2 limitations: (a) most of the effects produced by the interaction of 3 or more variables could not be quantified and evaluated; and (b) the nonlinear effects for the variables could not be evaluated.

In addition, because the technique for estimating material characterization constants (3) from the indirect tensile test was not available, this screening experiment was limited primarily to an evaluation of tensile strength. In the development of techniques

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for estimating modulus of elasticity, Poisson's ratio, and failure strains, there were minor changes in the testing equipment and procedures that prevented the estimation of these material constants for the mixtures evaluated in the screening experiment. Thus, a more complete followup study was conducted (5). The primary objectives of this study included (a) the examination of how changes in a number of independent variables affected certain dependent or response variables and (b) the development of a method of predicting the variations in these responses with changes in the independent variables. The first was accomplished by analyses of variance and the second was obtained from regression analyses.

EXPERIMENTAL PROGRAM

This program was designed to investigate 7 different factors considered to affect the tensile properties of asphalt-treated materials. A central composite design (6, 7, 8) was utilized, and it allowed the evaluation of nonlinear effects of 6 of the 7 factors. The factors and levels selected for this investigation are given in Table 1.

Selection of Factors

Two aggregate types that exhibited relatively extreme characteristics were selected. The gravel was a naturally occurring, subrounded, nonporous aggregate with a relatively smooth surface texture. The limestone aggregate, on the other hand, was a naturally occurring, porous aggregate with angular particles and a relatively rough surface texture when crushed.

The gradation curves for the fine, medium, and coarse-graded mixtures are shown in Figure 1. The fine, medium, and coarse gradations were identified by 2-mm, 4-mm, and 6-mm particles. These dimensions represent the diameter of the particle that was larger than 60 percent of the particles in the total mixture.

The temperature-viscosity relationships for the AC-5, AC-10, and AC-20 asphalt-cements are shown in Figure 2. The 3 levels were specified by the slope of the line connecting the viscosity at a temperature of 140 F and the viscosity at a temperature of 275 F, which was determined by the equation

$$\text{Slope} = \frac{\log\,(V140) - \log\,(V275)}{\log\,(140) - \log\,(275)}$$

TABLE 1

LEVELS OF FACTORS USED IN REGRESSION EQUATIONS

Factor	Classification	Description	Levels Used in Regression Equations
Aggregate type	Qualitative	Crushed limestone	A(-1) = 0
		gravel	A(+1) = 2
Aggregate gradation[a]	Quantitative	Fine	B(-1) = 2
		Medium	B(0) = 4
		Course	B(+1) = 6
Asphalt viscosity[a]	Quantitative	AC-5	C(-1) = 8.5
		AC-10	C(0) = 9.0
		AC-20	C(+1) = 9.7
Asphalt content, percent	Quantitative	Low-low	D(-2) = 4.0
		Low	D(-1) = 5.5
		Medium	D(0) = 7.0
		High	D(+1) = 8.5
		High-high	D(+2) = 10.0
Mixing temperature, deg F	Quantitative	Low	F(-1) = 250
		Medium	F(0) = 300
		High	F(+1) = 350
Compaction temperature, deg F	Quantitative	Low	G(-1) = 200
		Medium	G(0) = 250
		High	G(+1) = 300
Curing temperature, deg F	Quantitative	Low	H(-1) = 40
		Medium	H(0) = 75
		High	H(+1) = 110

[a] See Figures 1 and 2 for method of determining levels.

where V140 and V275 are the viscosities at 140 and 275 F. The AC-5, AC-10, and AC-20 asphalt-cements were identified by slopes of 8.5, 9.0, and 9.7 respectively.

The levels of asphalt content were chosen on the basis of the results of the screening experiment so that an optimum asphalt content could be obtained. Medium levels were also included in this experiment for the remaining quantitative variables. Aggregate type was a qualitative variable, i.e., a variable in which the different levels could not be arranged in order of magnitude (7). Therefore, no medium level was specified for aggregate type.

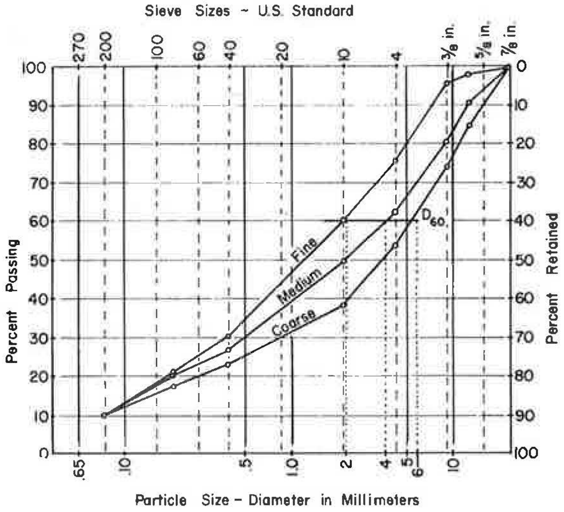


Figure 1. Gradation curves for aggregate mixtures.

Parameters Evaluated

In this study the following variables were evaluated: tensile strength, total tensile strain at failure, and modulus of elasticity. The development of the equations for these 3 variables is presented in another report (3). The value of the modulus of elasticity was obtained from a portion of the load-total deformation curve that was essentially linear.

Preparation and Testing Procedure

All asphalt-treated materials were mixed for 3 minutes and compacted in a Texas gyratory-shear molding press to form a cylindrical specimen with a nominal 4-in. diameter and 2-in. height. Following compaction, the specimens were allowed to cool to room temperature and their densities were determined. Then the specimens were cured for 14 days at the designated curing temperature. At the end of the curing period, the specimens were tested in indirect tension at 75 F and at a loading rate of 2.0 in./min. The test and equipment are described in detail in other reports (2, 3, 4).

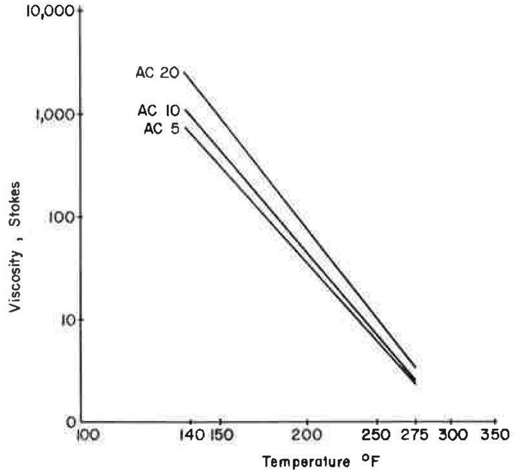


Figure 2. Temperature-viscosity relationship for asphalt cements.

Statistical Design and Analysis

This design consisted of a 2^7 full factorial with 128 possible combinations of the 7 factors, which allowed the analysis of main effects and interaction effects, and 52 wall points and 4 center points that allowed curvilinear effects to be evaluated.

The analysis consisted of an analysis of variance to determine the significance of main effects, interaction effects, and nonlinear effects produced by the 7 independent factors and a regression analysis to develop predictive equations for estimating the tensile properties of asphalt-treated materials for a given set of the 7 independent variables.

ANALYSIS

There were a number of factors and interactions that significantly affected the tensile strength, tensile failure strain, and modulus of elasticity of asphalt-treated materials; however, not all of these effects had practical significance. In other words, the effect, although measurable, was not large and probably would make no effective difference in the engineering application of the results. The effects judged to have practical meaning corresponded to a probability level of 0.5 percent for tensile strength and modulus of elasticity and 5 percent for total tensile strain. Those factors and their interactions of practical engineering significance to tensile strength, total tensile strain, and modulus of elasticity are given in Tables 2, 3, and 4 respectively. The effects that are listed as B_Q and D_Q were quadratic or nonlinear effects due to gradation and asphalt content respectively.

TABLE 2

ANALYSIS OF VARIANCE FOR TENSILE STRENGTH AT 75 F

Source of Variation[a]	Degree of Freedom	Mean Squares	F-Value	Significance Level (percent)
BD	1	137,615	299.80	0.5
G	1	105,580	230.01	0.5
D	1	59,391	129.39	0.5
D_Q(quadratic)	1	45,525	99.18	0.5
C	1	29,900	65.14	0.5
BDG	1	16,199	35.29	0.5
B_Q(quadratic)	1	15,185	33.08	0.5
ABD	1	14,699	32.02	0.5
B	1	12,368	26.94	0.5
BG	1	6,065	13.21	0.5
Experimental error	79	459.0		

[a] A = aggregate type; B = aggregate gradation; C = asphalt viscosity; D = asphalt content; F = mixing temperature; and G = compaction temperature.

TABLE 3

ANALYSIS OF VARIANCE FOR TENSILE STRAIN AT FAILURE AT 75 F

Source of Variation[a]	Degree of Freedom	Mean Squares ($\times 10^{-6}$)	F-Value	Significance Level (percent)
G	1	3.133	19.06	0.5
AD	1	1.723	10.48	0.5
D	1	1.307	7.95	1
A	1	0.901	5.48	2.5
Experimental error	64	0.1644		

[a] A = aggregate type; B = aggregate gradation; C = asphalt viscosity; D = asphalt content; F = mixing temperature; and G = compaction temperature.

TABLE 4

ANALYSIS OF VARIANCE FOR MODULUS OF ELASTICITY AT 75 F

Source of Variation[a]	Degree of Freedom	Mean Squares	F-Value	Significance Level (percent)
BD	1	103.2	191.33	0.5
G	1	75.0	139.10	0.5
D	1	48.4	89.77	0.5
C	1	20.3	37.73	0.5
D_Q(quadratic)	1	20.3	37.61	0.5
BDG	1	18.8	34.91	0.5
B_Q(quadratic)	1	12.4	22.99	0.5
ABD	1	6.5	11.99	0.5
A	1	5.1	9.50	0.5
Experimental error	79	0.539		

[a] A = aggregate type; B = aggregate gradation; C = asphalt viscosity; D = asphalt content; F = mixing temperature; and G = compaction temperature.

One of the best methods of obtaining an overall view of the variation of a particular dependent variable or response created by changes in the levels of the significant main effect and interactions is to formulate the functional relationship that exists between a dependent variable and a number of independent variables. Unfortunately, this relationship is usually too complicated to be described in simple terms. If there is no prior knowledge of its form, the function is approximated by some simple polynominal function that contains the appropriate variables and is valid over some limited ranges of the variables involved. Such a mathematical function can be extremely valuable for predicting the values of dependent variables based on knowledge of the independent variables (9).

In this study an approximation of the functional relationship between the dependent and independent variables was obtained by combining in the form of a polynominal those main effects, quadratic effects, and interaction effects that were found in the analysis of variance to be of practical engineering significance.

A stepwise regression analysis was performed to develop equations that provided an acceptable estimate of the various dependent variables measured in the experiment. These equations can be used to make estimates of the different dependent variables within some standard error for combinations of the independent variables. Included with the equations are the standard error of estimate, $\hat{S}_r$, and the coefficient of determination, R^2. The terms A, B, C, D, and G are the levels of the various factors used in the experiment (Table 1).

It should be noted, however, that the predictive capabilities of the regression equations are valid only for the conditions and factors studied, i. e., those factors and levels given in Table 1. The use of any levels outside this factor space is not recommended.

The equation for tensile strength, psi, at 75 F is

$$
\begin{aligned}
S_T = {} & 150.8 - 5.027(B - 4.0) + 26.037(C - 9.1) - 12.691(D - 7.0) \\
& + 0.574(G - 250.0) - 10.929(B - 4.0)(D - 7.0) + 3.572(A - 1.0)(B - 4.0) \\
& (D - 7.0) - 0.0688(B - 4.0)(G - 250.0) - 0.0750(B - 4.0)(D - 7.0)(G - 250.0) \\
& - 3.2775(B - 4.0)^2 - 11.545(D - 7.0)^2 \qquad (1)
\end{aligned}
$$

$\hat{S}_r = \pm 28$

$R^2 = 0.782$

The equation for total tensile strain at failure, micro-units, at 75 F is

$$
\begin{aligned}
\epsilon_T = {} & 1,372.9 + 96.28(A - 1.0) + 63.60(D - 7.0) - 3.147(G - 250.0) \\
& + 63.563(A - 1.0)(D - 7.0) \qquad (2)
\end{aligned}
$$

$\hat{S}_r = \pm 380$

$R^2 = 0.310$

The equation for modulus of elasticity, 1×10^5 psi, at 75 F is

$$
\begin{aligned}
E = {} & 3.531 - 0.248(A - 1.0) + 0.6605(C - 9.1) - 0.3646(D - 7.0) \\
& + 0.01523(G - 250.0) - 0.2993(B - 4.0)(D - 7.0) + 0.07491(A - 1.0)(B - 4.0) \\
& (D - 7.0) - 0.002557(B - 4.0)(D - 7.0)(G - 250.0) - 0.09857(B - 4.0)^2 \\
& - 0.2570(D - 7.0)^2 \qquad (3)
\end{aligned}
$$

$\hat{S}_r = \pm 0.853 \times 10^5$

$R^2 = 0.729$

The prediction capabilities of these 3 regression equations were established by several indicators and tests. Included among the indicators were multiple correlation coefficient, coefficient of determination, coefficient of variation, and standard error of estimate. The multiple correlation coefficient, which is generally denoted as R, is a measure of the linearity of the fit between the data and the regression equation, while the coefficient of determination R^2 indicates the portion of the total variation in the response variable that can be explained by the regression equation. The coefficient of variation is an indicator of the relative variation that can be expected. The standard error of estimate, $\hat{S}_r$, is the standard deviation of the errors of estimation. Normally, approximately two-thirds of the errors associated with the observed data will be less than the standard error of estimate, only about one-third of the errors will be more. In addition, under the same conditions, approximately 95 percent of the data will fall within a region bounded by 2 lines drawn parallel to the line of regression at a vertical distance of $\pm 1.96\ \hat{S}_r$.

One of the tests used to evaluate the regression equation was a test for lack of fit. The test essentially consisted of a significance test comparing the residual mean squares with the experimental error variance. The residuals for the regression equation contained all the available information on the failure of the fitted model to properly explain the observed variation in the response variable. If the model was correct; i.e., if the model fit the data, then the residuals contained only random variation that approximately equalled the experimental error variation. However, if the model was incorrect, the residuals contained systematic as well as random variations that were greater than the experimental error variation. The F-test for significance, then, indicated at some probability level ($\alpha = 0.01$ in this study) whether the regression equation properly explained the variation in the response variable.

The values of the indicators discussed as well as the results of the test for lack of fit are given in Table 5. Each regression equation was evaluated through the use of the indicators and a test for lack of fit. The parameters for tensile strength and modulus of elasticity (Table 5) indicate that the prediction capability of the regression equations was adequate. On the other hand, it is evident that the regression equation for total tensile strain was questionable; however, there was no significant lack of fit. The equation included the 3 factors of aggregate type (factor A), asphalt content (factor D), and compaction temperature (factor G). In this case a decision has to be made concerning the use of the equation. There are 2 alternatives. The first is to abandon the use of the equation and use the overall mean value of 1,370 micro-units as an estimate of the total tensile strain at failure. The basic argument for this approach is that because $R^2 = 0.310$ the equation explains only about 31 percent of the total variation in total tensile strain. The second alternative is to accept the equation with the reservation that there can be substantial variation in total tensile strain as evidenced by the relatively large standard error of estimate $\hat{S}_r = \pm 318$. The primary argument for this second approach is that a better approximation of total tensile strain than the mean can be obtained because there were 4 factors and their interactions that were found to be of practical engineering significance. On this basis, it is recommended that the regression equation be utilized.

TABLE 5

PARAMETERS FOR EVALUATING REGRESSION EQUATIONS

Response Variable	Correlation Coefficient	Coefficient of Determination	Coefficient of Variation (percent)	Standard Error of Estimate	Is There Significant Lack of Fit?
Tensile strength	0.8845	0.7823	14.2	±28.0	No
Total tensile strain	0.5564	0.3096	29.5	±318	No
Modulus of elasticity	0.8536	0.7286	20.8	$\pm 0.853 \times 10^5$	No

DISCUSSION OF RESULTS

Indirect Tensile Strength at 75 F

The variables included in the equation are aggregate type (factor A), aggregate gradation (factor B), asphalt viscosity (factor C), asphalt content (factor D), and compaction temperature (factor G). Table 6 gives estimated tensile strengths for different combinations of the 5 factors. Based on data given in this table, plots were developed indicating the relationship between asphalt content and compaction temperature for each aggregate at each of the 3 gradations. These are shown in Figure 3 for AC-5 asphalt cement. The effect of asphalt viscosity was linear; therefore, the tensile strengths for similar mixtures but with asphalts of different viscosities can be accounted for by adding the proper correction factors to the values obtained for AC-5 cement. For AC-10 and AC-20 asphalt cements, the correction factors are 13 and 31 psi respectively.

As shown in Figure 3, the specimens containing crushed limestone exhibited larger tensile strengths than specimens containing gravel. This behavior is attributed to the fact that the angularity, rough surface texture, and porosity of the limestone resulted in a better bond between the aggregate and the asphalt.

One of the striking aspects in all the relationships is the pronounced effect of compaction temperature on tensile strength; high compaction temperatures produced high

TABLE 6

ESTIMATED INDIRECT TENSILE STRENGTH OF AC-5 ASPHALT CEMENT AT 75 F

Compaction Temperature (deg F)	Asphalt Content (percent)	Crushed Limestone Aggregate (psi)			Gravel Aggregate (psi)		
		Fine	Medium	Coarse	Fine	Medium	Coarse
200	4.0	—	40.6	88.8	9.0	40.6	46.0
	4.5	2.3	66.0	103.5	38.0	66.0	67.8
	5.0	32.7	85.7	112.4	61.3	85.7	83.8
	5.5	57.3	99.5	115.5	78.7	99.5	94.1
	6.0	76.2	107.6	112.8	90.4	107.6	98.5
	6.5	89.2	109.9	104.4	96.4	109.9	97.2
	7.0	96.5	106.4	90.2	96.5	106.4	90.2
	7.5	98.0	97.2	70.2	90.9	97.2	77.3
	8.0	93.8	82.2	44.4	79.5	82.2	58.7
	8.5	83.8	61.4	12.9	62.3	61.4	34.3
	9.0	68.0	34.9	—	39.4	34.9	4.2
	9.5	46.4	2.5	—	10.7	2.6	—
	10.0	19.0	—	—	—	—	—
250	4.0	—	69.3	133.2	22.1	69.3	90.3
	4.5	19.2	94.7	144.1	54.9	94.7	108.4
	5.0	53.3	114.4	149.2	81.9	114.4	120.6
	5.5	81.7	128.2	148.6	103.1	128.2	127.1
	6.0	104.2	136.3	142.1	118.5	136.3	127.9
	6.5	121.1	138.6	130.6	128.2	138.6	122.8
	7.0	132.1	135.2	112.0	132.1	135.2	112.0
	7.5	137.4	125.9	88.3	130.2	125.9	95.4
	8.0	136.9	110.9	58.8	122.6	110.9	73.0
	8.5	130.6	90.2	23.5	109.2	90.2	44.9
	9.0	118.5	63.6	—	90.0	63.6	11.0
	9.5	100.7	31.3	—	65.0	31.3	—
	10.0	77.1	—	—	34.3	—	—
300	4.0	—	98.0	177.5	35.2	98.0	134.6
	4.5	36.0	123.4	184.7	71.7	123.4	148.9
	5.0	73.9	143.1	186.0	102.5	143.1	157.5
	5.5	106.0	156.9	181.6	127.4	156.9	160.2
	6.0	132.3	165.0	171.5	146.6	165.0	157.2
	6.5	152.9	167.3	155.5	160.1	167.3	148.4
	7.0	167.7	163.9	133.8	167.7	163.9	133.8
	7.5	176.7	154.6	106.3	169.6	154.6	113.5
	8.0	180.0	159.6	73.1	165.7	139.6	87.4
	8.5	177.4	118.9	34.1	156.0	118.9	55.5
	9.0	169.1	92.3	—	140.6	92.3	17.8
	9.5	155.1	60.0	—	119.4	60.0	—
	10.0	135.2	21.9	—	92.4	21.9	—

Note: Tensile strengths for mixtures with AC-10 and AC-20 asphalt cements can be obtained by adding 13 and 31 psi respectively to the values in this table.

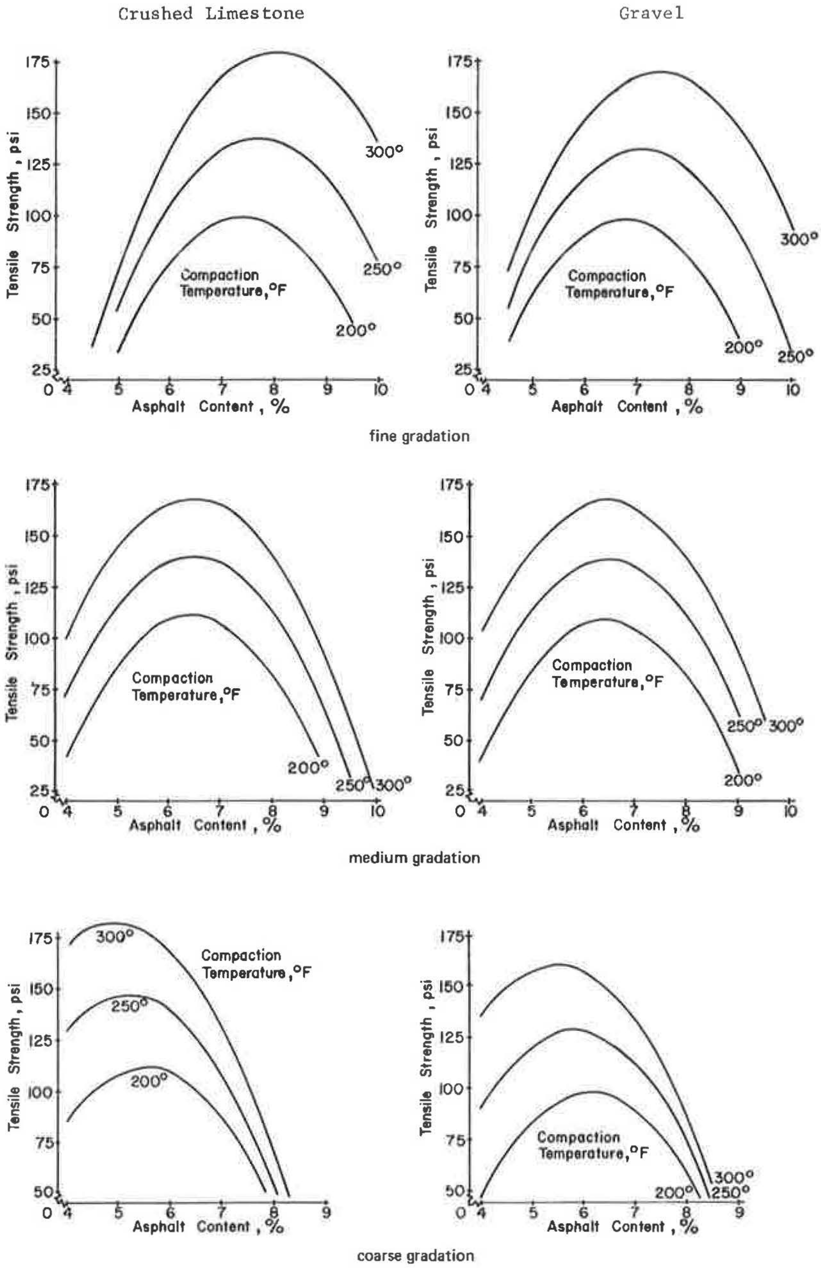


Figure 3. Prediction curves for tensile strength of AC-5 asphalt cement at 75 F.

tensile strengths. In addition, an optimum asphalt content occurred for each gradation of both aggregates; however, this optimum shifted slightly with increasing compaction temperatures for the fine and coarse gradations. For the fine gradations, the optimum asphalt content increased with increased compaction temperatures. On the other hand, for the coarse gradations, the optimum decreased with increased compaction; and for the medium gradation, the optimum asphalt content remained essentially constant. It

TABLE 7

ESTIMATED TOTAL TENSILE STRAIN AT FAILURE AT 75 F

Asphalt Content	Crushed Limestone (μ in.^{2})			Gravel (μ in.^{2})		
	200 F	250 F	300 F	200 F	250 F	300 F
4.0	1,435	1,275	1,120	1,245	1,090	930
4.5	1,435	1,275	1,120	1,310	1,150	995
5.0	1,435	1,275	1,120	1,370	1,215	1,060
5.5	1,435	1,275	1,120	1,435	1,280	1,120
6.0	1,435	1,275	1,120	1,500	1,340	1,185
6.5	1,435	1,275	1,120	1,565	1,405	1,250
7.0	1,435	1,275	1,120	1,625	1,470	1,310
7.5	1,435	1,275	1,120	1,690	1,535	1,375
8.0	1,435	1,275	1,120	1,755	1,595	1,440
8.5	1,435	1,275	1,120	1,815	1,660	1,505
9.0	1,435	1,275	1,120	1,880	1,725	1,565
9.5	1,435	1,275	1,120	1,945	1,785	1,630
10.0	1,435	1,275	1,120	2,010	1,850	1,695

can also be seen that the optimum asphalt content was higher for the specimens containing finer graded aggregates.

There are several factors involved in an explanation of the relationships shown in Figure 3. First, higher compaction temperatures produced greater fluidity of the asphalt cement, which allowed movement of the asphalt cement during compaction, thereby producing better distribution of the asphalt in the mixture and creating thinner films of asphalt connecting the aggregate particles.

The optimum asphalt contents for the finer graded mixtures were higher because more asphalt was required to cover the larger surface area associated with finer gradations. In addition, the increase in the optimum asphalt content with increased compaction temperatures was due to the fact that with increased fluidity during compaction the distribution of the asphalt was so improved that more of the fine particles could be bound together by asphalt films.

For the coarse graded mixtures, the optimum asphalt content decreased with increased compaction temperature because of the increased fluidity that allowed the aggregate particles to be adequately coated and connected with a smaller quantity of asphalt.

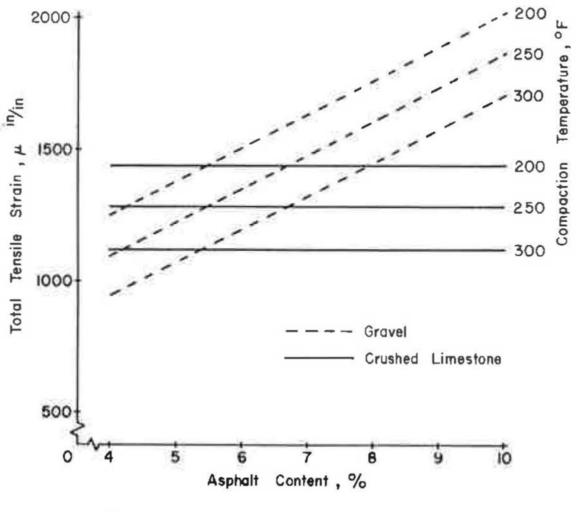


Figure 4. Prediction curves for total tensile strain at 75 F.

Total Tensile Strain at Failure at 75 F

Estimates of the total tensile strain based on the regression equations are given in Table 7, and a plot graphically illustrating the estimates is shown in Figure 4. Figure 4 shows that asphalt content had no effect on the total tensile strain of a mixture containing crushed limestone aggregate. On the other hand, for gravel-asphalt mixtures, the total tensile strain increased with increasing amounts of asphalt. For both aggregate types, the compaction temperature had a noticeable effect on total tensile strain; increased compaction temperature produced a decrease in the tensile strain at failure. This decrease in strain is attributed to the fact that the increased fluidity of the asphalt during compaction at the higher temperatures resulted in improved distribution of the asphalt with thinner films connecting aggregate particles. Because deformation occurs primarily in the asphalt, these thinner films result in smaller strains.

The difference in the behavior of mixtures containing the 2 aggregate types is also attributed to the thickness of the asphalt films connecting the aggregate particles. The crushed limestone, which is highly porous, readily absorbed excess asphalt and thus tended to produce asphalt films of essentially the same thickness regardless of asphalt content. Thus, it would be expected that the failure strain would be essentially constant for all the asphalt-crushed limestone mixtures. The gravel, on the other hand, is relatively nonporous and does not tend to absorb the available asphalt. Therefore, as the amount of asphalt in the gravel mixture increased, the thickness of the asphalt films connecting the aggregate particles increased. The thicker asphalt films then allowed larger deformations to occur, resulting in larger strains.

Modulus of Elasticity at 75 F

A review of the modulus of elasticity equation shows that only 5 of the 7 variables were practically significant. These variables were aggregate type (factor A), aggregate gradation (factor B), asphalt viscosity (factor C), asphalt content (factor D), and

TABLE 8

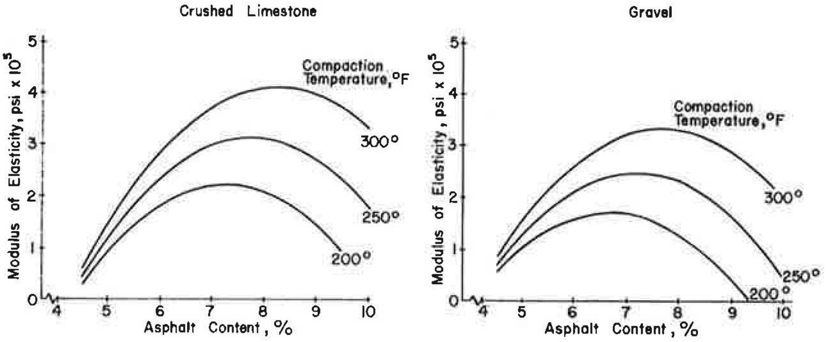
ESTIMATED MODULUS OF ELASTICITY VALUES OF AC-5 ASPHALT CEMENT AT 75 F

Compaction Temperature (deg F)	Asphalt Content (percent)	Crushed Limestone Aggregate (1 x 10^5 psi)			Gravel Aggregate (1 x 10^5 psi)		
		Fine	Medium	Coarse	Fine	Medium	Coarse
200	4.0	—	1.401	2.485	—	0.906	1.091
	4.5	0.300	1.926	2.763	0.554	1.430	1.519
	5.0	0.942	2.322	2.913	1.046	1.826	1.818
	5.5	1.456	2.589	2.934	1.410	2.094	1.989
	6.0	1.841	2.728	2.827	1.645	2.233	2.032
	6.5	2.098	2.739	2.591	1.752	2.243	1.946
	7.0	2.226	2.621	2.226	1.731	2.125	1.731
	7.5	2.226	2.374	1.734	1.581	1.879	1.388
	8.0	2.098	1.999	1.112	1.302	1.504	0.916
	8.5	1.840	1.496	0.362	0.896	1.000	0.316
	9.0	1.455	0.864	—	0.360	0.368	—
	9.5	0.941	0.103	—	—	—	—
	10.0	0.298	—	—	—	—	—
250	4.0	—	2.163	4.014	—	1.667	2.619
	4.5	0.422	2.687	4.164	0.676	2.192	2.919
	5.0	1.192	3.083	4.186	1.296	2.588	3.091
	5.5	1.834	3.351	4.079	1.788	2.855	3.134
	6.0	2.347	3.490	3.844	2.151	2.994	3.049
	6.5	2.732	3.500	3.480	2.386	3.005	2.835
	7.0	2.988	3.382	2.988	2.492	2.887	2.492
	7.5	3.116	3.136	2.367	2.470	2.640	2.022
	8.0	3.115	2.761	1.618	2.320	2.265	1.422
	8.5	2.985	2.257	0.740	2.040	1.762	0.694
	9.0	2.728	1.625	—	1.633	1.180	—
	9.5	2.341	0.865	—	1.097	0.369	—
	10.0	1.826	—	—	0.432	—	—
300	4.0	—	2.924	5.542	—	2.429	4.148
	4.5	0.544	3.449	5.565	0.798	2.953	4.320
	5.0	1.442	3.845	5.459	1.546	3.349	4.364
	5.5	2.212	4.112	5.224	2.166	3.617	4.279
	6.0	2.853	4.251	4.861	2.657	3.756	4.066
	6.5	3.365	4.262	4.369	3.020	3.766	3.724
	7.0	3.749	4.144	3.749	3.254	3.648	3.254
	7.5	4.005	3.897	3.001	3.360	3.402	2.655
	8.0	4.132	3.522	2.124	3.337	3.027	1.928
	8.5	4.130	3.019	1.118	3.185	2.523	1.072
	9.0	4.000	2.387	—	2.906	1.891	0.088
	9.5	3.742	1.626	—	2.497	1.131	—
	10.0	3.355	0.737	—	1.961	0.242	—

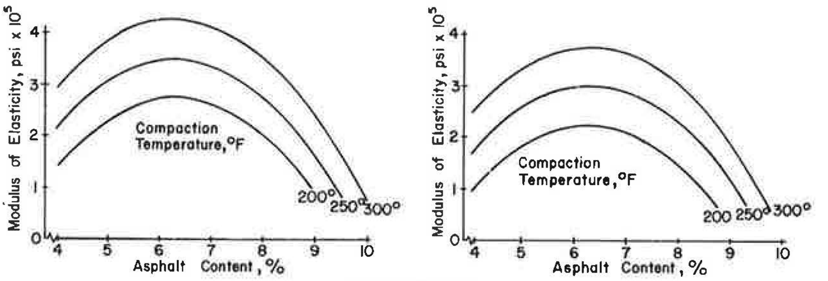
Note: Modulus of elasticity estimates for mixtures with AC-10 and AC-20 asphalt cements can be obtained by adding 0.330 and 0.790 respectively to the values in this table.

compaction temperature (factor G). A number of moduli of elasticity for a variety of combinations of the 5 factors were estimated by utilizing the equation and are given in Table 8. In addition, plots indicating the relationship between asphalt content and compaction temperature for the 3 gradations and for each aggregate type are shown in Figure 5 for AC-5 asphalt cement. These relationships will change linearly with change in asphalt viscosity because the effect of asphalt viscosity was linear. Therefore, estimates of modulus of elasticity for mixes with AC-10 or AC-20 can be obtained by adding 0.330×10^5 and 0.790×10^5 respectively to the values obtained for AC-5.

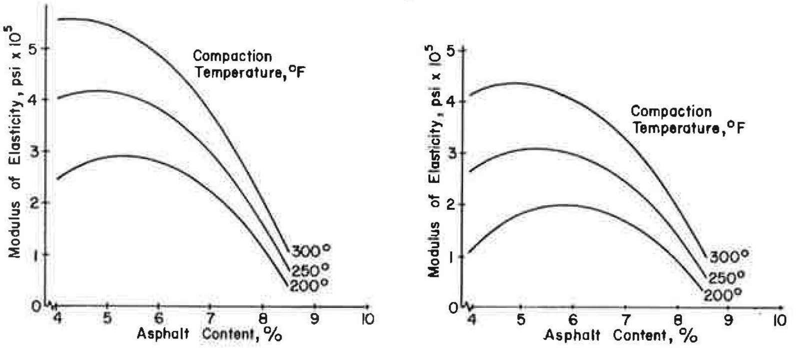
The relationships between asphalt content and compaction temperature for the different gradations of crushed limestone and gravel are similar to those for tensile strength. In all the figures, the effect of compaction temperature is evident. In addition, optimum asphalt contents are evident and shift slightly with increased compaction temperature for the fine- and coarse-graded mixtures. The optimum asphalt content for fine-graded mixtures increased with increased compaction temperature, while the optimum for coarse-graded mixtures decreased with higher compaction temperatures. In addi-



fine gradation



medium gradation



coarse gradation

Figure 5. Prediction curves for modulus of elasticity of AC-5 asphalt cement at 75 F.

tion, it may be noted that specimens containing coarser graded aggregate exhibited larger modulus values.

Because there were similarities in the trends observed for modulus of elasticity (Fig. 5) and tensile strength (Fig. 3), the explanation of the relationship between tensile strength and the 5 significant (or important) variables can also be used to explain the relationship between modulus of elasticity and the same 5 variables.

There were, however, 2 distinct differences in the results for modulus of elasticity and tensile strength. First of all, although there were no differences in tensile strengths between asphalt-treated mixtures containing crushed limestone or gravel, there were differences in moduli of elasticity for the 2 different aggregate mixtures. Second, coarse-graded mixtures containing gravel generally exhibited higher moduli of elasticity but lower tensile strengths. Both are attributable to the difference in the failure strain behavior of mixtures containing the 2 aggregates.

Because modulus of elasticity is defined as the ratio of stress to strain, the modulus of elasticity from the indirect tensile test can be regarded as the ratio of tensile strength to tensile strain at failure. When this analogy is used, the modulus of elasticity of crushed limestone-asphalt mixtures should be related linearly to tensile strength because these mixtures exhibited constant tensile failure strains (Fig. 4). On the other hand, although the gravel-asphalt mixtures exhibited tensile strengths higher than those of the crushed limestone-asphalt mixtures, lower moduli of elasticity were produced because of greater tensile strains for the gravel-asphalt mixtures.

The second difference noted can be explained in a similar manner. The optimum asphalt content for the coarse-graded gravel-asphalt mixture was smaller than for the medium- and fine-graded gravel-asphalt mixtures; therefore, the tensile strains were lower and offset the lower tensile strengths, producing higher moduli of elasticity.

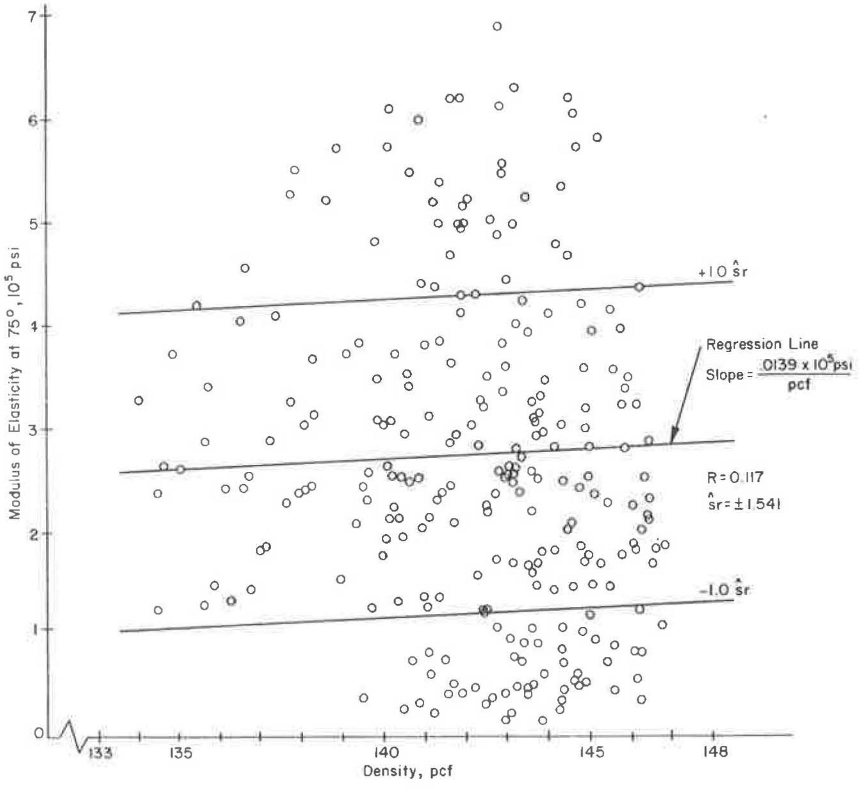


Figure 6. Relationship between modulus of elasticity and density of mix.

Correlation of Tensile Properties and Density

The density of an asphalt mix is of concern in design; however, it was difficult to control in this experiment because it was dependent on the factors involved in the mixing and compaction procedures. Thus, density was not an independent variable but was considered as a dependent or response variable similar to modulus of elasticity and tensile strength.

In general, it is considered that density is related to material properties, with higher densities corresponding to higher strengths. If this were true, then there should have been a good correlation between density and both modulus of elasticity and tensile strength.

In order to study this relationship, a correlation analysis was conducted that indicated that there was no trend or correlation between either tensile strength and density (Fig. 6) or modulus of elasticity and density (Fig. 7). The linear regression relationship relating the 2 tensile properties to density are included in the figure along with the correlation coefficient R and standard error of estimate $\hat{S}_r$. The slopes of the lines are very flat, indicating that the modulus of elasticity and strength were relatively independent of density.

Within the range of densities that occurred in this study, these results indicate that an increase in density may or may not be indicative of an increase in the modulus of elasticity or tensile strength. On the other hand, it has been shown that mixture variables such as aggregate type, gradation, asphalt viscosity, asphalt content, and compaction temperature can have a great influence on both the modulus of elasticity and tensile strength. Therefore, changes in density alone cannot be used as a measure of expected changes in tensile properties of the mix but must be accompanied by careful consideration of the factors involved in the mix design.

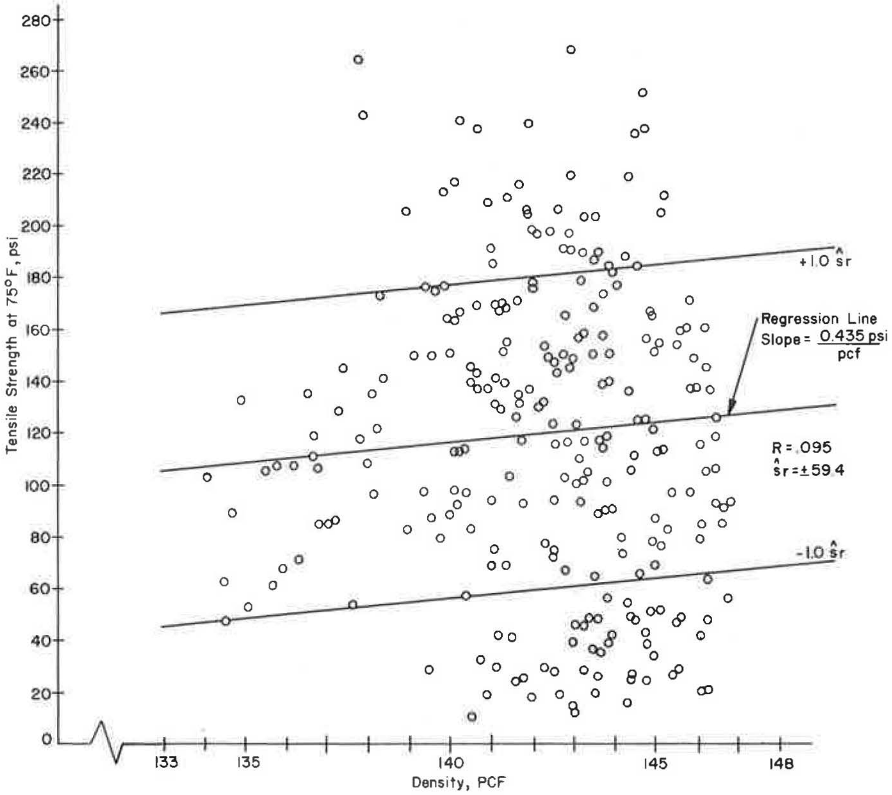


Figure 7. Relationship between tensile strength and density of mix.

CONCLUSIONS AND RECOMMENDATIONS

This paper presents equations for estimating the modulus of elasticity, tensile strength, and total tensile strain at failure for a variety of asphalt-treated materials at 75 F. The equations for modulus of elasticity and tensile strength are shown to be very reliable and can be used to predict the variations in these 2 responses with changes in aggregate type, gradation, asphalt viscosity, asphalt content, and compaction temperature. The equation for total tensile strain is not as reliable as the other two, but it can be used to provide better estimates of tensile strain for these materials than those currently available. In all cases, the decision to use these equations must be based on the error that can be tolerated. Nevertheless, it is felt that these equations are the best estimators currently available.

Estimates of modulus of elasticity, tensile strength, and total tensile strain at failure for a variety of combinations of the independent variables are given in Tables 6 through 8. Graphical representations of the interrelationships among the response variables, modulus of elasticity, tensile strength, and tensile strain, and a number of the mix variables are shown in Figures 3, 4, and 5 respectively and indicate the dominant effect of compaction temperature on all 3 tensile properties.

A number of variables must be considered when the tensile properties of asphalt-treated materials are evaluated. When the modulus of elasticity and tensile strength of such mixtures are evaluated, consideration must be given to aggregate type, gradation, asphalt viscosity, asphalt content, and compaction temperature. Aggregate type, gradation, and compaction temperature must also be considered when total tensile strain at failure is evaluated.

Because optimum asphalt contents were detected for the modulus of elasticity and tensile strength, it would appear that the indirect tensile test can be used to obtain optimum mix designs. The optimum asphalt content obtained, however, will depend on the aggregate type, aggregate gradation, and compaction temperature. Although a set of design tests may be needed to complement the results, the tables presented can be used to provide preliminary estimates and narrow the range of investigation in the laboratory.

Because there was no correlation between either modulus of elasticity and density or tensile strength and density for the conditions of the test, changes in density alone cannot be used as a measure of expected changes in tensile properties of the mix but must be accompanied by careful consideration of the factors involved in the mix design.

The effect of compaction temperature could explain some of the differences observed in the past between laboratory and field results because most laboratory procedures involve preparation of materials at certain fixed compaction temperatures. If the mixtures are compacted in the field at temperatures much different from those used in laboratory tests, then certainly, as evidenced by the results of the study, the mixture cannot be expected to perform in the field as predicted in the laboratory. Closer control of compaction temperature in the field through specification requirements could produce mixture properties closer to those design mixtures established in the laboratory and could substantially increase uniformity of mixtures along the length of the highway.

Present laboratory test procedures should be extended to include the evaluation of effects of changes in compaction temperature.

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