Fundamental Comparison of the Flexural and Indirect Tensile Tests

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A study is described that was undertaken to complete a fundamental evaluation and comparison of the indirect tensile test and the beam test by using basic theoretical equations and finite element analysis techniques. A finite element analysis was completed so that consideration could be given to the effects of factors such as (a) Poisson's ratio, loading strip width, and diameter and (b) Poisson's ratio, height-length ratio, and deflection location on the results of the indirect tensile and beam tests, respectively. Comparisons between theoretical and finite element solutions indicate that the values of modulus of elasticity and tensile stresses and strains can be overestimated or underestimated by using theoretical equations. For the beam test, the use of the basic beam deflection formula to estimate the fundamental properties results in underestimated modulus and tensile stress values and overestimated tensile strain values. On the other hand, the use of Hondros' equations for the indirect tensile test resulted in underestimates for all three properties. This analysis ultimately resulted in the development of modified equations for estimating fundamental properties for both test configurations. By using available beam and indirect tensile test data, it was found that the modified equations yielded similar modulus values, which were significantly higher than those obtained from the basic equation, the same slope on a log cycles-log strain basis (i.e., fatigue coefficient C), and a closer agreement between fatigue results (i.e., number of cycles-tensile strain).

Theoretical structural design procedures for flexible pavements are generally based on preventing two types of failures: cracking (fatigue failure) and permanent deformation. It is generally accepted that fatigue cracking is controlled by limiting the tensile strain or stress at the bottom of the pavement layers whereas pavement deformation is controlled by limiting the compressive strain at the top of the subgrade (1).

In either case it is essential that reliable information be available concerning the fundamental properties and tensile characteristics of the stabilized materials projected for use in pavement sections. Consequently, a method of evaluating tensile properties such as modulus of elasticity and Poisson's ratio for base and subbase materials is necessary in order to conduct a rational evaluation of stabilized materials by using layered system theory (1,2).

Several different test methods are currently used in the evaluation of the fundamental properties of pavement materials. Two of these test methods have been used principally for estimating the tensile characteristics of pavement materials: the indirect tensile test and the beam test.

As an aid to the designer, it is important that any relations among the various test procedures be developed so that the material characterization data from each can be used more effectively. This approach is essential because tests conducted on similar materials often yield different material characterization constants--e.g., modulus of elasticity and Poisson's ratio. This situation, of course, leads to the acceptance of certain tests or test results by one agency and not by another. If the results of the various test procedures could be correlated, the data could be interchanged so as to expand significantly the available material characterization data.

CURRENT STATUS OF KNOWLEDGE

Indirect Tensile Test

The indirect tensile test was developed simultaneously but independently by Carneiro and Barcellos (3) in Brazil and Akazawa (4) in Japan. Hondros (5) extended the equations for the indirect tensile test configuration to allow for a load over a surface area. Subsequently, Hadley, Hudson, and Kennedy (2,6) developed a direct method by which fundamental properties could be determined from the results of the indirect tensile test. This method expanded the application of Hondros' equation, making it possible to obtain estimates of Poisson's ratio, modulus of elasticity, tensile strength, and tensile strains for cohesive materials.

The indirect tensile test involves loading a cylindrical specimen with a single or repeated compressive load by using a stainless steel loading strip, which is applied parallel to and along the vertical diameter plane, as shown in Figures 1 and 2.

Beam Test

The beam test involves the application of a load configuration that results in the bending of a beam specimen. There are two standard methods for applying load to a simply supported beam. The load may be applied as two equal, concentrated loads at the third points of the beam or as a single concentrated load at the midpoint of the beam (see Figure 3).

In general, the flexural formula is used to estimate tensile stresses in a beam. Various forms of the bending deflection formulas are used to estimate modulus and tensile strains by using the applied loads and the resulting center or third point beam

Figure 1. Cylindrical specimen with compressive load being applied.

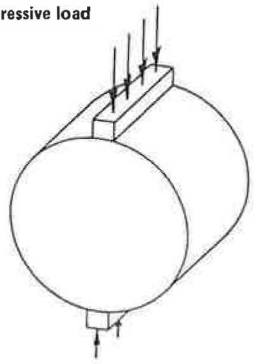


Figure 2. Specimen failing under compressive load.

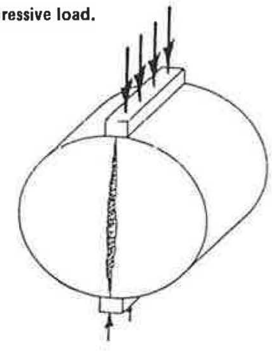


Figure 3. Loading conditions for beam test.

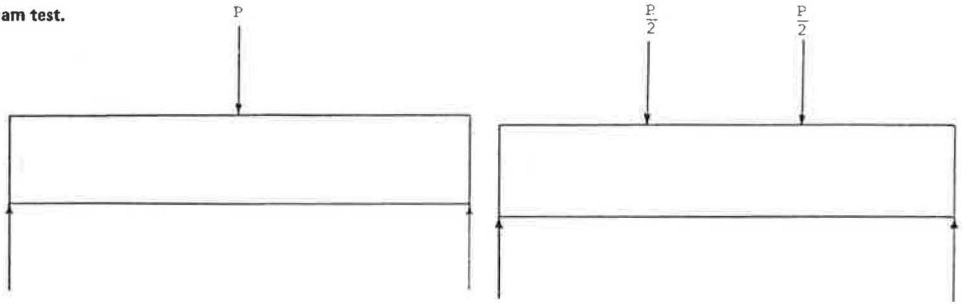
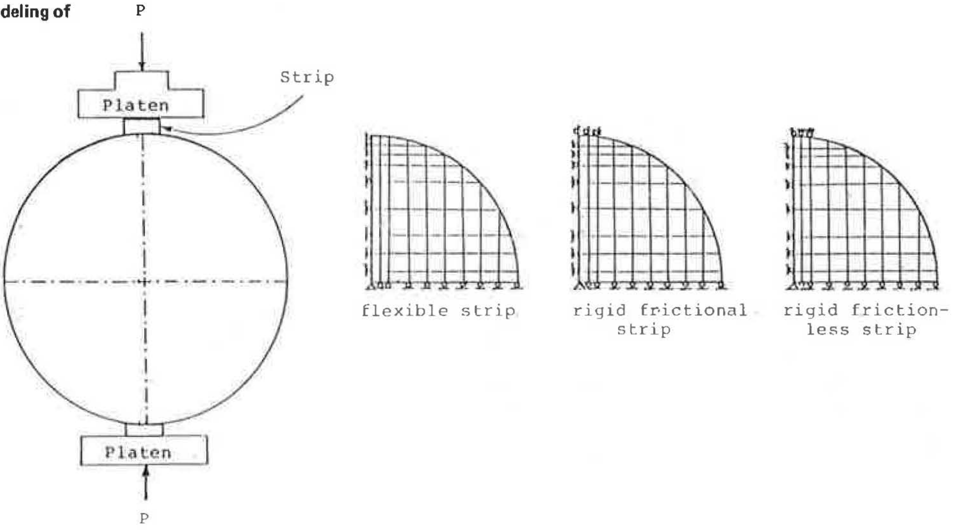


Figure 4. Finite element modeling of indirect tensile test.



deflections. It should be noted, however, that the resulting deflected shape of the beam is a function of both flexural (or bending) effects and shear force effects. If the deflection of a beam under a given load is used in estimating material properties such as modulus and tensile strains, both effects should be considered.

METHOD OF ANALYSIS

A finite element method of analysis was used in this study to determine the response of the stabilized construction material under varying boundary loading conditions for the two test configurations (7). The construction material was assumed to have the same properties in tension and compression, and a plane stress condition was selected for the evaluation of indirect tensile and beam test configurations. The details of the analysis are summarized in the following sections.

Indirect Tensile Test

The finite element model consisted of a cylindrical specimen with a 15.25-cm (6.0-in.) diameter and 2.54-cm (1.0-in.) thickness loaded with a compressive load through a stainless steel loading strip 1.27 cm (0.5 in.) in width.

Three loading strips--a flexible loading strip, a rigid frictional loading strip, and a rigid frictionless loading strip--were evaluated with the finite element model. The flexible strip was modeled by using a uniform contact pressure and the rigid strips were modeled by using a uniform displacement of the strips. The frictionless strip allows for unrestrained lateral movement of the specimen; the frictional strip assumes the development of sufficient friction between the specimen and the strip to ensure no lateral displacement of the portion of specimen under the strip. The finite element model for the indirect tensile test, a two-dimensional representation of a quarter section, is shown in Figure 4.

Beam Test

The finite element model consists of a beam 38.10 cm (15.0 in.) in length, 2.54 cm (1.0 in.) in width, and 8.89 cm (3.5 in.) in height that is exposed to a third point loading condition (see Figure 5). The width of the loading heads and supports was 0.64 cm (0.25 in.).

Two loading configurations were investigated in the evaluation of the beam test. One configuration consisted of loads and supports at the neutral axis and the other of loads and supports at extreme fiber locations (see Figure 6). In addition, two other conditions were investigated in the analysis: bending effects only and bending plus shear effects. The bending configuration of the finite element model of the specimen was induced by displacements under the load strips based on bending and shear--i.e., $\delta = \delta_{bending} + \delta_{shear}$--and bending only--i.e., $\delta = \delta_{bending}$--which were determined from theoretical equations and based on the applied load.

Selection of Material Properties

The required data for the finite element computer program consisted of the fundamental engineering properties of modulus of elasticity (E) and Poisson's ratio (μ) (7). A modulus value of 4165 MPa

(604,000 psi) and a Poisson's ratio value of 0.348 were used and are representative of a hot-mix asphaltic concrete.

MODEL RESULTS

To compare the stress and strain values predicted by theoretical equations with those obtained from the finite element analysis, the appropriate predicted values were plotted on the same figure so that direct comparisons could be accomplished. The comparisons for the indirect tensile test are shown in Figures 7-10, and the comparisons for the beam test are shown in Figures 11-14. The results of each test are discussed and summarized in the following sections.

Indirect Tensile Test

Figures 7-10, which include the plots of Hondros' theoretical values versus finite element predicted stresses and strains (radial along horizontal in Figures 7 and 9 and tangential along vertical axes in Figures 8 and 10), show a close comparison between the stress and strain values obtained for the finite element model with a flexible loading strip and those determined by Hondros' theoretical equations. In this comparison the deviation percentages for the flexible loading strip model were less than 2.5 percent for radial and tangential stresses and strains along horizontal axes and less than 3.5 percent for radial and tangential stresses and strains along vertical axes.

On the other hand, greater differences between finite element predicted values and Hondros' theoretical values were obtained for those models with frictional and frictionless rigid loading strips. In the latter case, differences of up to 68 percent were found along the horizontal axis and up to 475 percent along the vertical axis.

Since boundary loading conditions similar to those of the rigid-frictional case are expected to be developed in the indirect tensile test because of the use of rigid (curved) loading strips, it can be surmised that Hondros' equations would underestimate the tensile stresses by approximately 14 to 60 percent.

It should be noted that the rigid type of boundary loading condition did not change significantly the stress and strain distributions but rather resulted generally in greater stress and strain values.

Figure 5. Finite element modeling of beam test.

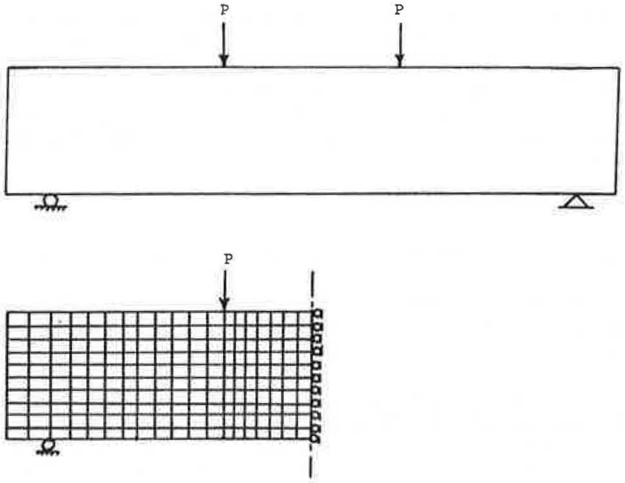


Figure 6. Two idealized loading configurations for beam test.

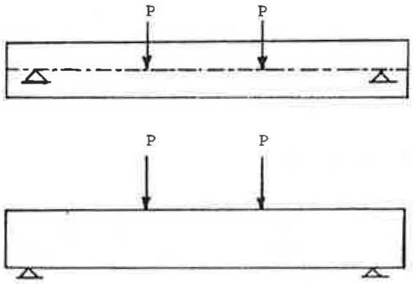


Figure 7. Radial stresses along horizontal axis of asphaltic specimen subjected to indirect tensile test.

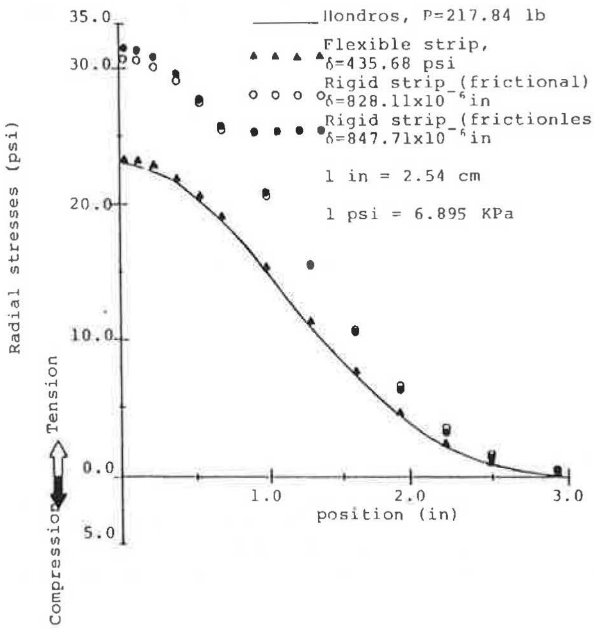


Figure 8. Tangential stresses along vertical axis of asphaltic specimen subjected to indirect tensile test.

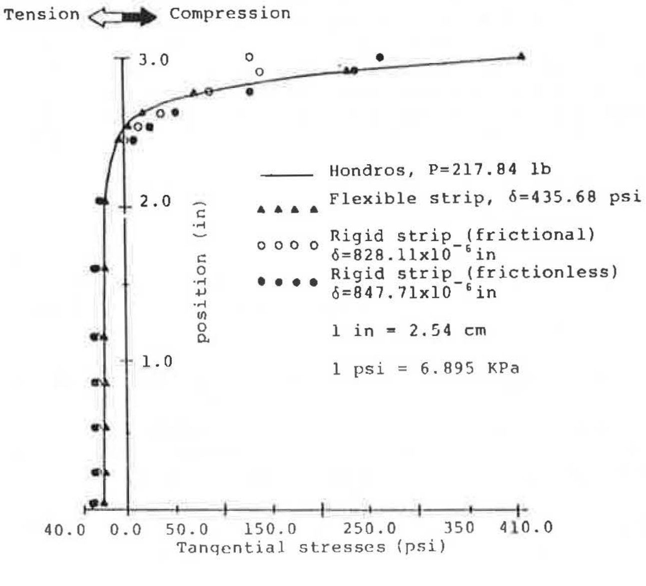


Figure 9. Radial strains along horizontal axis of asphaltic specimen subjected to indirect tensile test.

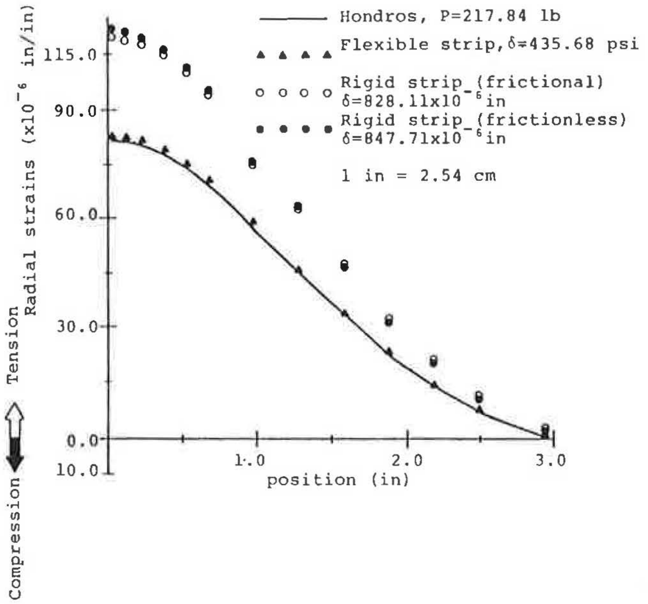


Figure 10. Tangential strains along vertical axis of asphaltic specimen subjected to indirect tensile test.

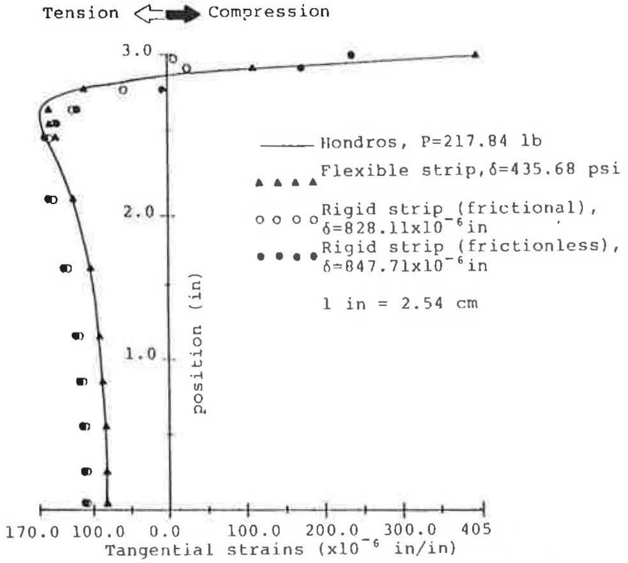


Figure 11. Stress distribution of asphaltic specimen subjected to beam test, where deflection of beam is based on bending and shear.

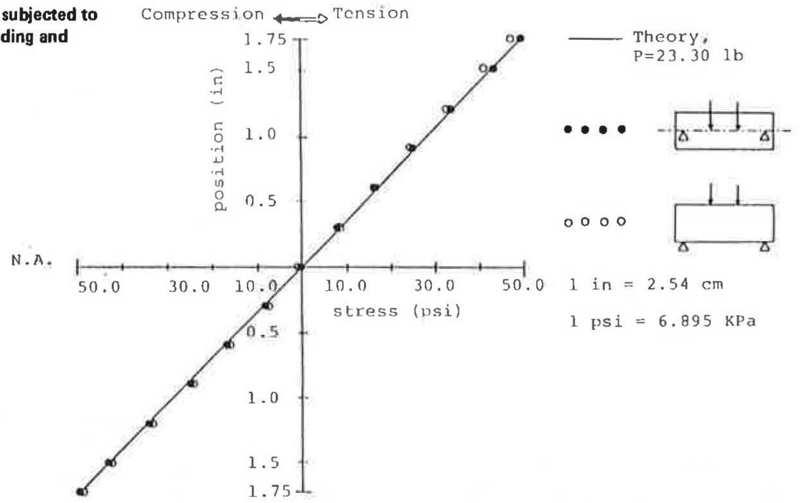


Figure 12. Strain distribution of asphaltic specimen subjected to beam test, where deflection of beam is based on bending and shear.

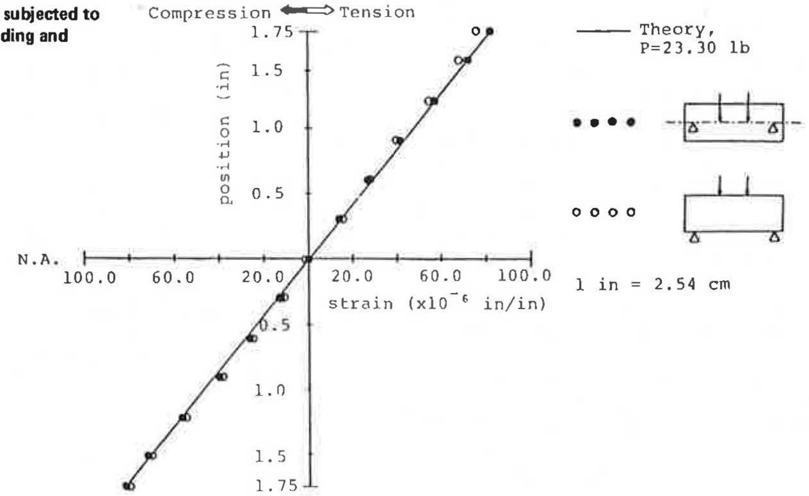


Figure 13. Stress distribution of asphaltic specimen subjected to beam test, where deflection of beam is based on bending.

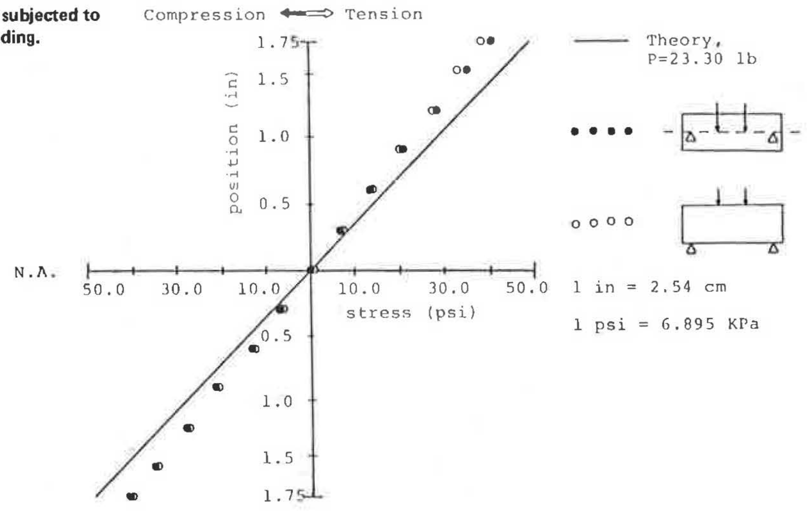
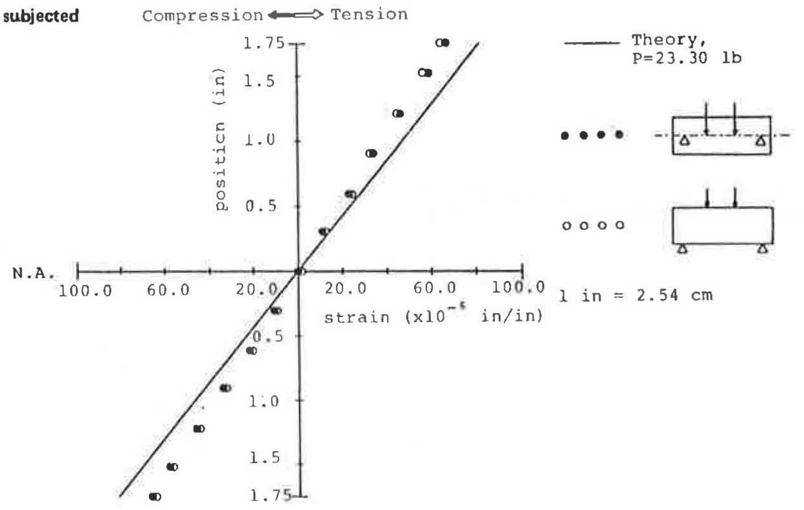


Figure 14. Strain distribution of asphaltic specimen subjected to beam test, where deflection is based on bending.



Beam Test

In Figures 11 and 12, a close comparison can be observed between theoretical and finite element predicted stresses and strains of a beam, supported and loaded at the neutral axis, with induced displacements based on a combination of bending and shear effects ($\delta = \delta_{bending} + \delta_{shear}$). In this case the deviation between the finite element results and the theoretical results was less than 5 percent for both tensile stresses and strains.

From the same figures it can be ascertained that the stresses and strains developed in a beam, supported and loaded at the extreme fiber locations, with combined bending and shear ($\delta = \delta_{bending} + \delta_{shear}$), are greater than those for the beam supported and loaded at the neutral axis due to shifts in the location of the neutral axis of the finite element model produced by deflection of the model. In the latter case, the finite element predicted tensile stresses and strains are approximately 10 percent greater than those predicted by beam theory.

As shown in Figures 13 and 14, the stress and strain values for a beam supported and loaded at the extreme fibers were underestimated by 13 to 25 percent for the case in which the induced displacements are based on bending only ($\delta = \delta_{bending}$). For the asphaltic specimen supported and loaded at the neutral axis ($\delta = \delta_{bending}$), the deviation percentages between theoretical and finite element predicted values were about 17 to 20 percent. It should be noted that this is the form of equation normally used in material characterization and evaluations. In the same way, the use of this abbreviated flexural equation (i.e., considering bending effects only and excluding shear effects) would also result in underestimation of the modulus of the material tested in a flexural configuration.

RECOMMENDED CHANGES TO FUNDAMENTAL EQUATIONS

The results of the finite element analysis of the beam and indirect tensile test configurations point out the need to develop improved materials characterization equations for both tests. With this in mind, a subsequent finite element analysis was undertaken to aid in the development of changes needed in the equations.

In particular, the additional model study of the indirect tensile test included an evaluation of the effects of Poisson's ratio, width of loading strip, and diameter on the results of the finite element model. In addition, the expanded model theory for the beam test included the investigation of height-length ratio, Poisson's ratio, and location of measured beam deflection. From this analysis, the following equations were obtained. Because the equations presented here are based on finite element model analysis, they should be applicable to both static and resilient material evaluations.

Indirect Tensile Test

Poisson's ratio (μ), modulus (E), tensile stress (ST), and tensile strain (ϵ_T) are expressed as follows:

For an approximate diameter of 4 in.,

$$\mu = (0.0800R - 0.8590)/(0.0403 - 0.2851R) \quad (1)$$

$$E = (PD/xt)(0.0800 + 0.2970\mu + 0.425\mu^2) \quad (2)$$

$$ST = (0.1777 + 0.0223\mu)(P/t) \quad (3)$$

$$\epsilon_T = (0.5409 + 0.5161\mu)x \quad (4)$$

and, for an approximate diameter of 6 in.,

$$\mu = (0.0619R - 0.7515)/(0.0257 - 0.2182R) \quad (5)$$

$$E = (PD/xt)(0.0646 + 0.2357\mu + 0.0290\mu^2) \quad (6)$$

$$ST = (0.1400 + 0.0112\mu)(P/t) \quad (7)$$

$$\epsilon_T = (0.3696 + 0.6354\mu)x \quad (8)$$

where

P = applied load,
D = specimen diameter,
x,y = horizontal and vertical deformations resulting from applied load P,
t = specimen height, and
R = ratio of y/x.

Beam Test

For the beam test, flexural stress (σ_f), modulus (E_f), and tensile strain (ϵ_f) can be expressed as follows:

$$\sigma_f = 3aPK_4/K_1bt^2 \quad (9)$$

$$E_f = PaK_2(3\ell^2 - 4a^2)48IdK_3 \quad (10)$$

$$\epsilon_f = \sigma_f/E_f \quad (11)$$

where

$$K_1 = 1.005 + 2.195\ (1 + \mu)(t/\ell)^2$$

$$K_2 = 1.034 + 9.233\ (1 + \mu)(t/\ell)^2 - 46.828\ (1 + \mu)[(t/\ell) - 0.208]^2 - 0.389\mu$$

$$K_3 \begin{cases} = 1.00 \text{ if deflection is measured at third point} \\ = 0.835 + 0.115\ (t/\ell) \text{ if deflection is measured at center point} \end{cases}$$

$$K_4 \begin{cases} = 1.00 \text{ if deflection is measured at third point} \\ = 0.981 - 0.371\ (t/\ell) \text{ if deflection is measured at center point} \end{cases}$$

and

a = distance from reaction to applied load,
P = total load applied,
b = beam width,
t = beam height,
ℓ = reaction span length,
I = specimen moment of inertia, and
d = deflection resulting from the applied load.

VERIFICATION OF EQUATIONS

Material characterization information developed for the Louisiana Experimental Base Project (9,10) by the Asphalt Institute and Louisiana Tech University was used to provide checks on the two sets of equations. The resilient fatigue data for the indirect tensile test were obtained from repetitive tests by using a sine wave loading pattern of 1 Hz, and the beam test data were obtained by using a haversine loading pattern at 1 Hz but with a rest period during each cycle.

The results of the resilient-flexural fatigue beam tests on laboratory prepared specimens conducted by the Asphalt Institue are given in Table 1 (9). Similar resilient-fatigue values for laboratory-prepared specimens and field core indirect tension tests conducted by Louisiana Tech are given in Tables 2 and 3 (10). From the tables it can be seen that the modified equations yielded higher modulus estimates than the basic equations for both the beam and indirect tensile tests.

The modified indirect tensile test equations also yielded higher tensile strain estimates in the Louisiana Tech tests, but the modified beam equation produced lower tensile strain estimates. The results of a statistical analysis, given in Tables 4 and 5, indicate that there are no significant differences in the modulus estimates obtained from the two test configurations by using the modified equations whereas there was a significant difference in the modulus estimates obtained from the basic equations.

An additional check in the verification process included the relations between fatigue life and applied tensile strain for both sets of equations based on the Asphalt Institute and Louisiana Tech University fatigue data. The results of this comparison are presented in Figures 15-17. It can be seen that the fatigue curves developed from the modified equations fall above the basic equation curves for the indirect tensile test results of both the laboratory specimens and field cores by Louisiana Tech yet below the basic equation fatigue curve for the Asphalt Institute beam test. Consequently, it can be seen that the fatigue curves generated from the modified equations are shifted more closely to one another (see Figure 18). In addition, the

Table 1. Asphalt Institute flexural fatigue test results for laboratory-prepared specimens (beam test).

		Basic Equation		Modified Equation	
Applied Stress (psi)	Cycles to Failure	Resilient Modulus[a] (psi)	Strain (10^{-6}in./in.)	Resilient Modulus[b] (psi)	Strain (10^{-6}in./in.)
182	1,380	2.30	792	3.55	396
184	7,600	3.46	539	5.35	269
144	9,491	2.71	532	4.19	266
174	14,600	3.09	563	4.77	281
124	18,597	2.97	416	4.59	208
130	46,000	4.03	321	6.23	160
102	67,825	2.82	365	4.36	182
103	136,830	4.25	243	6.57	121
101	154,212	3.81	266	5.89	133
103	206,800	4.98	207	7.70	103
76	279,000	4.73	161	7.31	80
51	766,800	4.48	113	6.92	56

Note: Data for single mix design. Test temperature was 77° F.

[a] Mean = 3.636 and variance = 0.7599.

[b] Mean = 5.619 and variance = 1.8176.

slopes of all fatigue curves (log N_f-log ε curves) are essentially the same (a value of $c \cong 3.0$) and the same resilient modulus values were obtained.

The differences between the fatigue curves (intercept N_f value) developed from the modified equations can be attributed to a basic difference in load application. In the beam test, the specimen is subjected to a haversine wave at 1 Hz, and a rest period is provided whereas the indirect tensile tests were conducted by using a sine wave of 1-Hz frequency. The rest period as well as the slightly faster load application (i.e., stress applied in a shorter time period in haversine waveform) could result in a greater resistance to fatigue.

CONCLUSIONS

The results of this study provide a mechanistic evaluation and comparison of theoretical and finite element predicted stresses and strains of the indirect tensile test and the beam test in their application to material characterization studies. Based on the results of the study, the following conclusions were made:

1. For the indirect tensile test, tensile stresses (σ), strains (ε), and modulus (E) are underestimated when Hondros' basic equation is used in estimating fundamental engineering properties.
2. For the beam test, the values of stresses and strains are overestimated and the modulus is underestimated when the beam displacements are substituted into a basic beam deflection formula based on bending only. Because of the closer correlations between the theoretical stresses and strains and the finite element stresses and strains obtained from the deflections based on bending and shear (i.e., $\delta = \delta_{bending} + \delta_{shear}$), it is obvious that shear effects should be considered in determining material properties.
3. The modified equations for estimating the fundamental material properties of construction materials developed from a finite element investigation yielded comparable fundamental material properties such as modulus (E) and fatigue regression coefficient (c) for the beam and indirect tensile tests.
4. The modified equations also yielded curves

Table 2. Louisiana Tech University indirect tensile test results for laboratory-prepared specimens.

			Resilient Test Results			
			Basic Equation		Modified Equation	
Applied Stress (psi)	Age at Test (days)	Cycles to Failure	Modulus[a] (psi)	Strain (10^{-6}in./in.)	Modulus[b] (psi)	Strain (10^{-6}in./in.)
44.8	112	721	4.62	158	5.16	207
44.9	112	975	4.84	139	5.88	182
29.1	35	1,742	3.16	136	3.84	178
28.7	112	1,922	4.49	96	5.46	126
28.8	112	1,932	3.35	129	4.06	169
28.4	112	2,247	4.51	95	5.48	125
28.9	112	2,362	4.32	100	5.24	131
29.0	112	2,446	4.43	97	5.39	127
28.8	112	2,868	4.50	95	5.47	125
29.2	35	2,934	4.21	102	5.11	134
28.7	112	3,166	3.11	138	3.56	181
29.0	112	4,481	5.00	86	6.07	113
28.5	112	4,922	5.17	83	6.29	109
28.4	343	6,446	5.01	85	6.09	112
28.1	112	7,124	6.33	68	7.69	89
28.9	343	7,696	2.89	149	3.52	195
28.0	112	8,900	4.37	98	5.31	129
28.7	112	10,547	4.20	102	5.10	134
28.3	112	11,706	4.70	91	5.71	120
28.4	112	15,392	5.36	80	6.51	105
12.9	112	21,950	2.97	63	3.61	83
28.1	112	28,619	5.73	75	6.96	98
28.3	112	33,642	5.75	75	6.98	98
12.6	112	39,490	3.58	53	4.36	69

Note: Variety of mix designs included. Test temperature was 77° F.

[a] Mean = 4.442 and variance = 0.8378.
[b] Mean = 5.369 and variance = 1.2670.

Table 3. Louisiana Tech University indirect tensile test results for asphalt field cores.

		Resilient Test Results			
		Basic Equation		Modified Equation	
Applied Stress (psi)	Cycles to Failure	Modulus[a] (psi)	Strain (10^{-6}in./in.)	Modulus[b] (psi)	Strain (10^{-6}in./in.)
44.8	977	3.955	163	4.794	214
46.2	1,822	5.001	134	6.049	176
44.6	1,869	4.356	154	5.290	202
54.2	2,405	7.804	105	9.476	138
39.2	2,440	3.601	162	4.078	213
38.5	2,646	4.538	128	5.518	168
29.1	2,872	3.609	119	4.387	156
45.6	3,117	5.064	133	6.164	174
29.4	3,373	4.245	101	5.147	133
43.7	3,411	5.231	143	6.005	188
28.6	4,619	4.263	101	5.178	132
29.0	8,924	3.661	117	4.444	154
29.3	11,651	4.934	87	5.989	114
12.5	16,756	3.578	53	4.347	69
12.6	18,199	4.168	64	3.626	83
28.7	18,324	6.576	65	7.996	88
12.7	18,824	2.828	67	3.436	88
18.6	24,277	5.310	53	6.451	69
18.8	30,071	6.329	44	7.694	58
18.8	35,637	5.604	50	6.807	65
12.7	39,083	2.976	64	3.619	83
18.4	42,819	5.630	50	6.851	65
12.6	45,725	2.639	77	3.208	101
12.4	48,194	3.113	61	3.780	80
12.6	51,283	4.728	40	5.742	53
12.7	69,845	2.962	64	3.600	84
12.4	72,046	2.335	81	2.834	106
12.6	78,659	6.843	28	8.328	36
12.7	78,947	3.451	55	4.195	72
13.0	81,560	5.236	36	6.374	47
9.1	130,344	1.988	67	2.416	88
12.7	556,770	3.927	48	4.778	63

Note: Test temperature was 77° F.

[a] Mean = 4.3894 and variance = 1.8621.
[b] Mean = 5.2688 and variance = 2.8415.

Table 4. Resilient modulus values for laboratory-prepared specimens: wearing-course material, Louisiana Experimental Base Project.

		Basic Equation			Modified Equation		
Agency	Test	Mean Value (psi 000s)	SD (psi 000s)	df	Mean Value (psi 000s)	SD (psi 000s)	df
Asphalt Institute	Beam	363.6	87.17	11	561.9	134.82	11
Louisiana Tech University	Indirect tensile	444.2	91.53	9	536.9	112.56	23

Note: Significant difference found for basic equation; no significant difference for modified equation.

Table 5. Resilient modulus values for laboratory-prepared specimens and field cores: wearing-course material, Louisiana Experimental Base Project.

			Modified Equation		
Agency	Test	Specimen	Mean Value (psi 000s)	SD (psi 000s)	df
Asphalt Institute	Beam	Laboratory	561.9	134.82	11
Louisiana Tech University	Indirect tensile	Field core	526.9	168.57	31

Note: No significant difference.

Figure 15. Fatigue results for beam test of laboratory-prepared specimens.

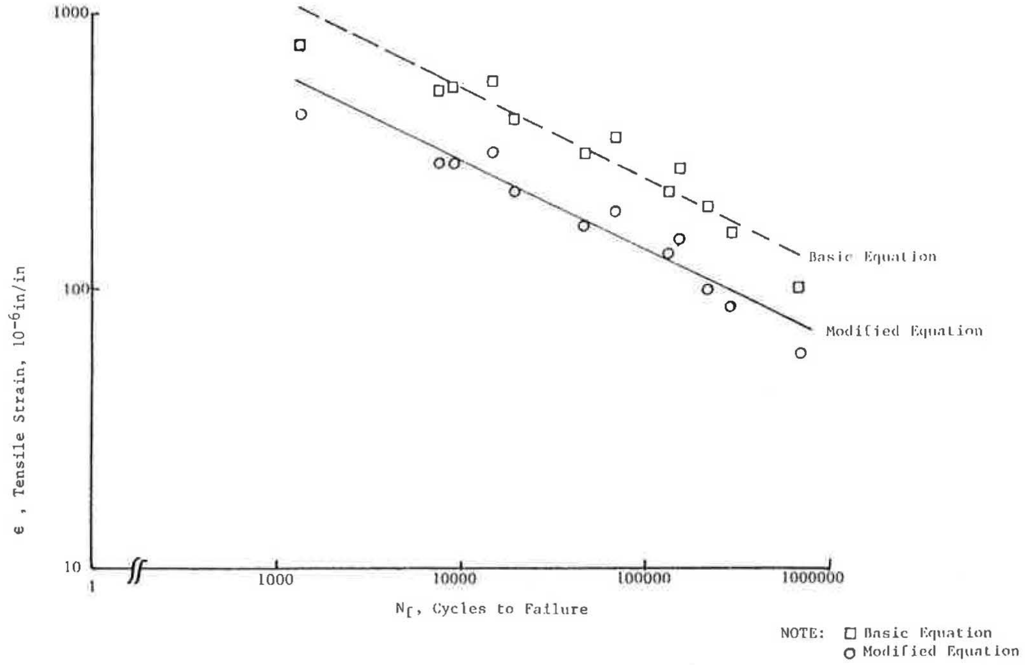
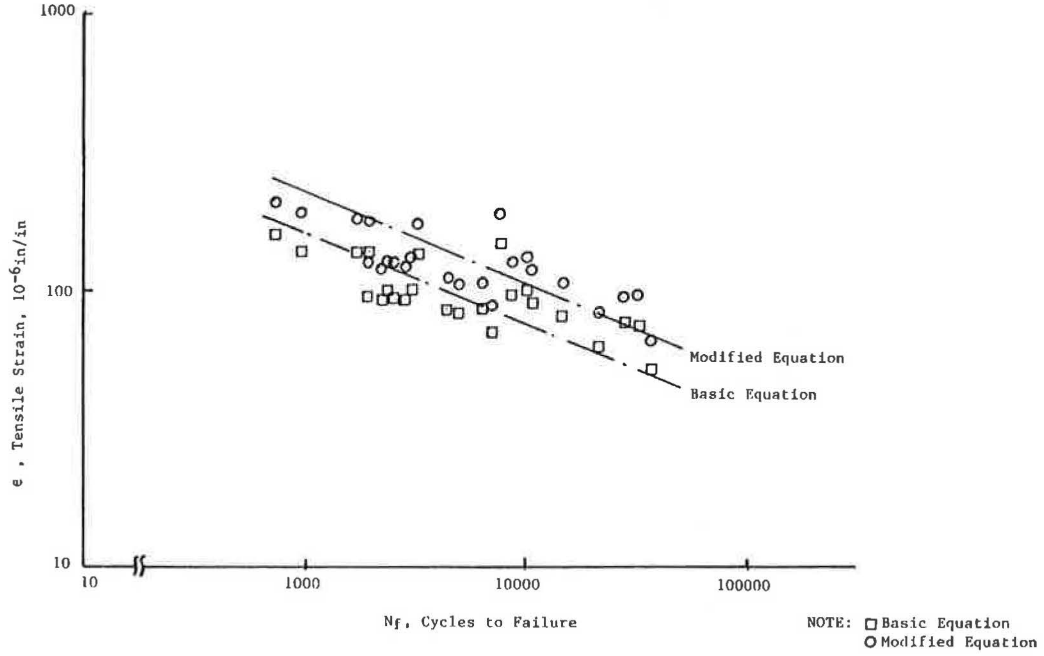


Figure 16. Fatigue results for indirect tensile test of laboratory-prepared specimens.



for fatigue versus tensile strain that were more closely related to one another.

ACKNOWLEDGMENT

The work presented in this paper is drawn from the findings of a research project concerned with fundamental engineering properties of construction materials, particularly related to the Louisiana Experimental Base Project. The work was sponsored by the Louisiana Department of Transportation and Development and the Federal Highway Administration, and their support is gratefully acknowledged. Many individuals provided assistance, and their contributions are gratefully acknowledged. Special thanks are extended to Jimmy Lyon, S. Shah, and James Melancon of the Louisiana Department of Transportation and Development and Ben Kallas of the Asphalt Institute, who provided technical liaison and support for the project. The work of Anis K. Martin in assembling the manuscript of the paper is gratefully acknowledged.

The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of

Figure 17. Fatigue results for indirect tensile test of field core specimens.

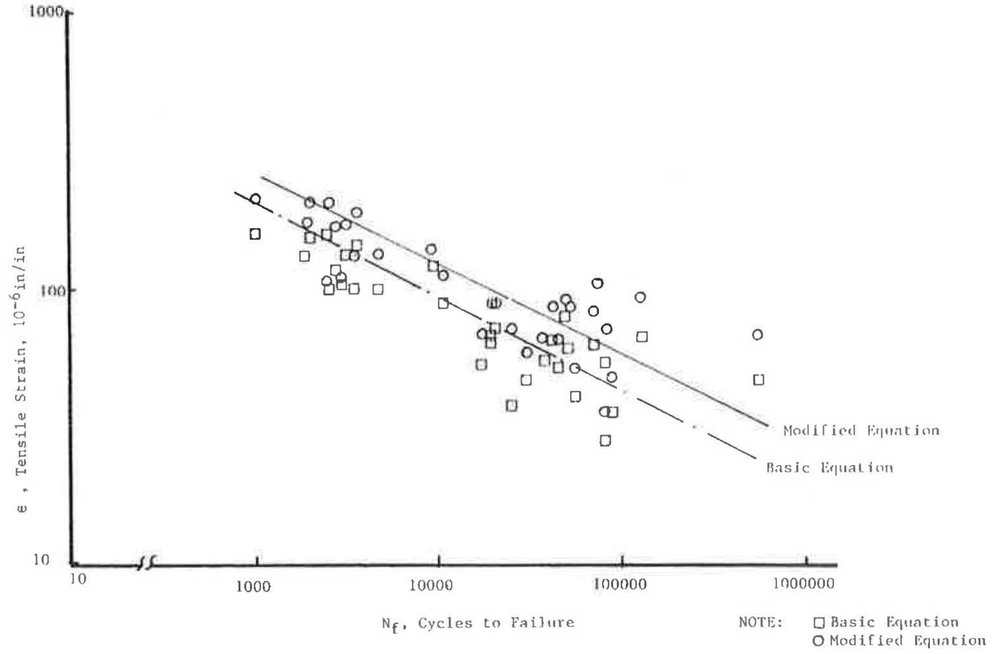
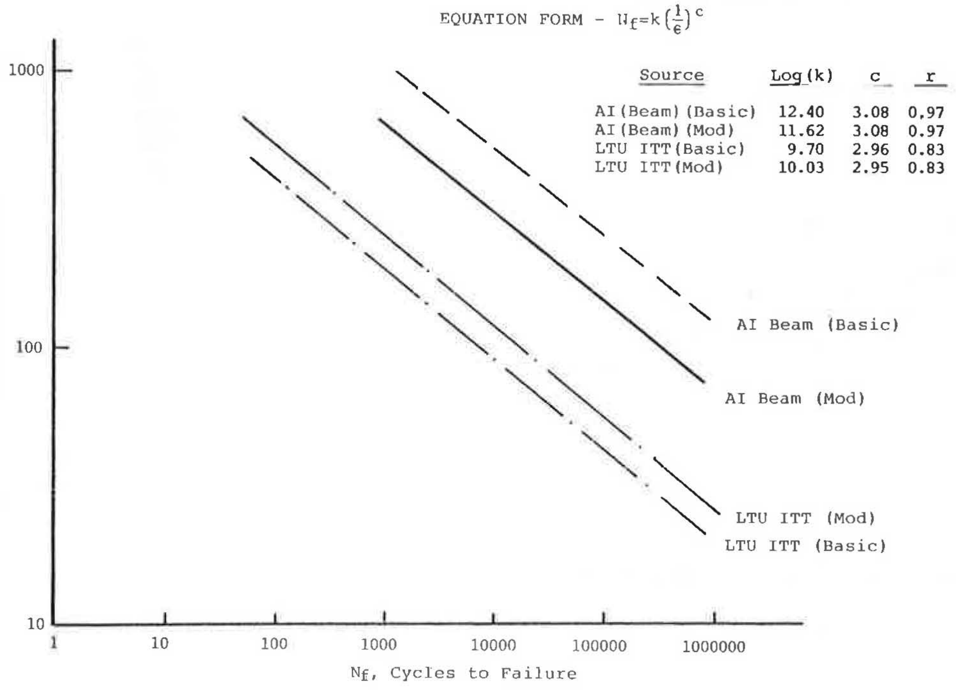


Figure 18. Comparison of fatigue results obtained by using basic and modified equation forms.



EQUATION FORM – $N_f=k\left(\frac{1}{\epsilon}\right)^c$

Source	Log (k)	c	r
AI(Beam)(Basic)	12.40	3.08	0.97
AI(Beam)(Mod)	11.62	3.08	0.97
LTU ITT(Basic)	9.70	2.96	0.83
LTU ITT(Mod)	10.03	2.95	0.83

the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures to Meet Structural Requirements.

Test for Efficiency of Mixing of Recycled Asphalt Paving Mixtures

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The increasing costs of construction materials, along with environmental conditions, have given great impetus to current interests in recycling. In recent years, reuse or recycling of existing pavement materials has emerged as a workable rehabilitation and maintenance alternative because it offers several advantages over the use of conventional materials and techniques. Although the equipment and technology of recycling have been developed, there still is no standardized or widely accepted method for testing recycled mixtures. The practice of using a small amount of recycling agent is coupled with the problem of quality control. There is no suitable method of detecting how well the recycling agent mixes with the aged pavement materials. A study is described whose primary objective was to develop a test method that could be conducted in the field with a minimum of equipment and training. As a result, the dye chemistry technique was found to be the most practical method of measuring the extent of mixing during a recycling operation. Ten field projects involving various plant types were conducted to demonstrate the application of such a technique to full-scale construction conditions. The overall mixing efficiency of a specific operation can be evaluated by statistically analyzing the resulting dye distributions. Consequently, the mixing process or plant design can be optimized by obtaining such information.

The need for efforts to conserve natural materials and improve methods and processes in the highway construction industry has greatly intensified since the realization of an imminent energy shortage. The problem of finding suitable virgin materials for pavements exists concurrently with the problem of disposing of spoils or solid wastes. One solution is to reuse or recycle existing materials for construction, rehabilitation, and maintenance purposes (1-4). The world has some 9 million miles of paved roads containing large quantities of quality aggregate and bitumen that in the past could not be reused. The economic value stored in the raw materials in existing roadways presents a new opportunity for the highway construction industry. FHWA indicates that there are more than 2 million miles of paved roads and streets in the United States, all of which are candidates for eventual recycling (5,6).

The term recycling is defined by the Asphalt Institute as "the reuse, usually after some processing, of a material that has already served its first-intended purpose in a roadway." The recycling or reuse of existing pavement materials for pavement rehabilitation, reconstruction, and maintenance is not a new concept. A wide variety of recycling approaches has emerged since 1915 (7,8). Asphalt as well as concrete pavements have been recycled, and quality improvement has often been accomplished by adding aggregate, asphalt, portland cement concrete, or a rejuvenating agent. In recent years the recycling of pavement materials has proved to be economically feasible and functionally successful. The state of the art of designing and constructing pavements composed of recycled materials has now advanced to a point where recycling is considered to be a workable rehabilitation and maintenance alternative.

The increase in recycling operations has created an awareness that the characteristics of the recycled material must ensure a quality pavement. One of the major concerns of engineers with regard to