LITERATURE REVIEW

SIMPLE TEST METHOD FOR POSSIBLE USE IN PREDICTING THE FATIGUE OF ASPHALTIC CONCRETE

by

J. R. Freeman, Jr.
Engineer Trainee

and

G. W. Maupin, Jr.
Research Engineer

Task C of Contract No. DOT-FH-11-8324, "Simple Procedure for Fatigue Characterization of Bituminous Concrete"

Virginia Highway and Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways and Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

February 1975
VHTRC 75-R30

LIST OF FIGURES

LIST OF TABLES

1718

LITERATURE REVIEW

SIMPLE TEST METHOD FOR POSSIBLE USE IN PREDICTING THE FATIGUE OF ASPHALTIC CONCRETE

by

J. R. Freeman, Jr.
Engineer Trainee

and

G. W. Maupin, Jr.
Research Engineer

It has been recognized for many years that fatigue is one of many mechanisms by which asphaltic concrete pavements fail. Experience and empirical design procedures such as those developed by Marshall and Hveem have enabled engineers to design mixtures against most common premature failure mechanisms such as rutting and bleeding, but due to the complex nature of fatigue failure it is difficult to analyze and to design pavements preventing fatigue failure.

It is possible to define the fatigue behavior of an asphaltic concrete by running a series of fatigue tests; however, the required equipment is very expensive and the testing time is usually in terms of weeks, which make routine fatigue testing and design impractical.

If fatigue behavior could be defined by a relatively simple, fast, and inexpensive test, many premature fatigue failures could be prevented.

PURPOSE

The purpose of this literature review was to examine simple test methods that possibly could be used to delineate the fatigue properties of asphaltic concrete. The literature review is one part of a multiphase project whose ultimate goal is the development of a simple test to predict the fatigue behavior of asphaltic concrete.

Four of the most promising simple tests for use in predicting the fatigue properties of asphaltic concrete will be analyzed in a laboratory investigation.

SIMPLE TESTS

Because fatigue failure usually is caused by repetitions of tensile stresses and strains, it is logical that the simple test should provide for testing in a tensile mode. The findings from the literature search which follow concentrate on but are not limited to the following items:

1. Tensile testing.
2. Simplicity of sample preparation.
3. Utilization of laboratory and pavement samples.
4. Sensitivity of test method to:
    - A. Aggregate shape, texture, and gradation.
    - B. Mineral filler.
    - C. Test temperature.
    - D. Rate of deformation.
    - E. Asphalt content and grade.
5. Predictive capability of fatigue behavior.

SIMPLE TESTS USED FOR ASPHALTIC CONCRETE

Indirect Tensile Test

The indirect tensile test was developed in 1953 by Carneiro and Barcellos of Brazil and Akazawa of Japan, working independently. The test was developed for use in testing cylindrical concrete specimens by applying compressive loads along a diametrical plane through two opposite loading heads. This loading condition produces a relatively uniform stress which acts perpendicular to the applied load plane and the specimen usually fails by splitting along the loaded plane.[1]

Timoshenko and Goodier[2] developed the theory showing stresses present in a circular disk when two equal and opposite forces act along the diametrical plane. Figure 1 shows the stresses developed in a circular disk when the forces are applied.

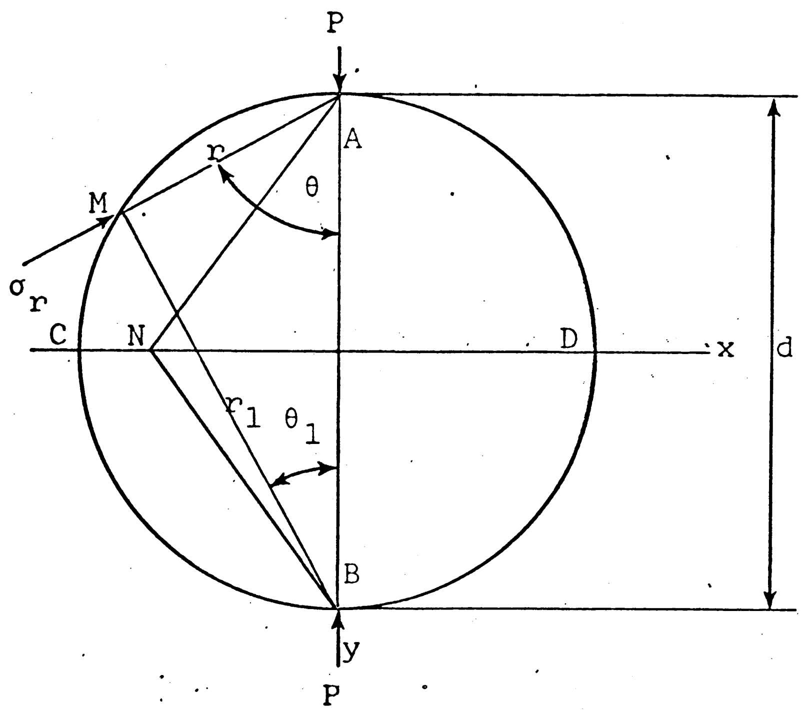

Figure 1. Stresses in a circular disk.[2]

The thickness of the plate is unity and the load, P, is assumed to be distributed uniformly over the unit thickness. Considering a situation where the disk is loaded only from the top, the stress, σ_r, at a point M can be determined by simple radial stress distribution. This simple compression stress is in the radial direction and can be computed by

$$\sigma_r = -\frac{2P}{\pi}\frac{\cos\theta}{r} \tag{1}$$

When two equal and opposite forces act on the disk, each force produces a simple radial stress distribution. Again using a point M, it would have two compressive forces acting on it in the directions r and r_1. These forces are equal to $\frac{2P}{\pi}\frac{\cos\theta}{r}$ for r and $\frac{2P}{\pi}\frac{\cos\theta_1}{r_1}$ for r_1. Since r and r_1 are perpendicular to each other, it can be shown that $\frac{\cos\theta}{r} = \frac{\cos\theta_1}{r_1} = \frac{1}{d}$, where d is the diameter of the disk. It can now be seen that the compressive forces acting in the direction of r and r_1 are equal and of magnitude $\frac{2P}{\pi d}$.

Timoshenko used this theory to develop equations for σ_x and σ_y along the horizontal diametrical axis. However, for use with the indirect tensile test, equations must be developed that can compute the x and y stresses for any point on the disk. These were developed by Frocht(3) using a system of rectangular stress components.

Frocht used the theory of Timoshenko in his development of the equations. His equation for simple radial compressive stress was the same as Timoshenko's except that he did not assume the thickness to be unity. Frocht's equation for σ_r is stated as:

$$\sigma_r = -\frac{2P}{\pi t}\frac{\cos\theta}{r} \tag{2}$$

where: t = the thickness of the disk.

Using this equation for simple radial compressive stress and the system of rectangular stress components shown in Figure 2, Frocht developed the equations for stresses in the x and y directions at any point to be

$$\sigma_x = \sigma'_r \sin^2\theta_1 + \sigma''_r \sin^2\theta_2 + \frac{2P}{\pi td} \tag{3}$$

$$\sigma_y = \sigma'_r \cos^2 \theta_1 + \sigma_r'' \cos^2 \theta_2 + \frac{2P}{\pi td} \qquad (4)$$

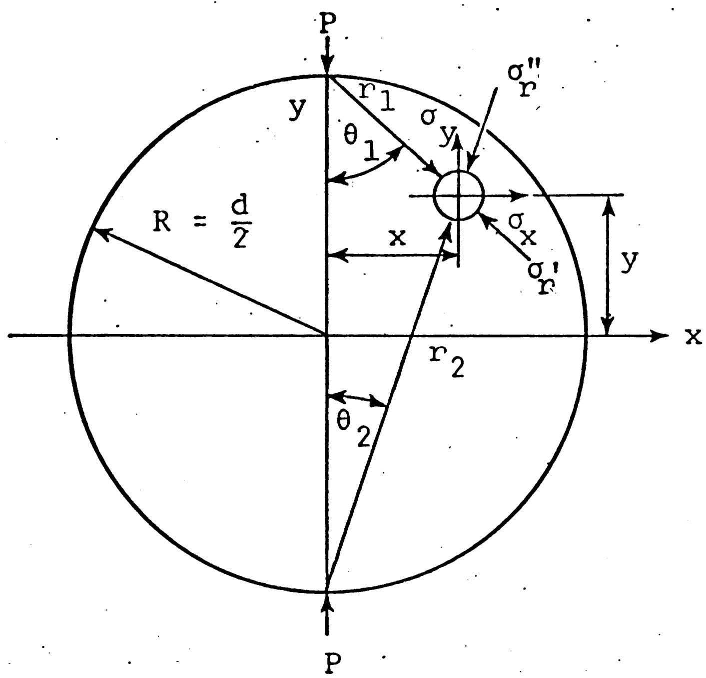

Figure 2. Sketch showing notation for rectangular stress components.(3)

By the substitution of various expressions into the equations, they can be simplified into the form

$$\sigma_x = \frac{-2P}{\pi t}\left(\frac{(R-y)x^2}{r_1^4} + \frac{(R+y)x^2}{r_2^4} - \frac{1}{d}\right) \qquad (5)$$

$$\sigma_y = \frac{-2P}{\pi t}\left(\frac{(R-y)^3}{r_1^4} + \frac{(R+y)^3}{r_2^4} - \frac{1}{d}\right) \qquad (6)$$

The stresses developed on the horizontal diametrical plane by use of the above equations are shown in Figure 3. The equations for these stresses are

$$\sigma_x = \frac{2P}{\pi td}\left(\frac{d^2 - 4x^2}{d^2 + 4x^2}\right)^2 \qquad (7)$$

$$\sigma_x = \frac{-2P}{\pi td}\left(\frac{4d^2}{(d^2 + 4x^2)^2} - 1\right) \qquad (8)$$

with σx being a tensile stress and σy being compressive.

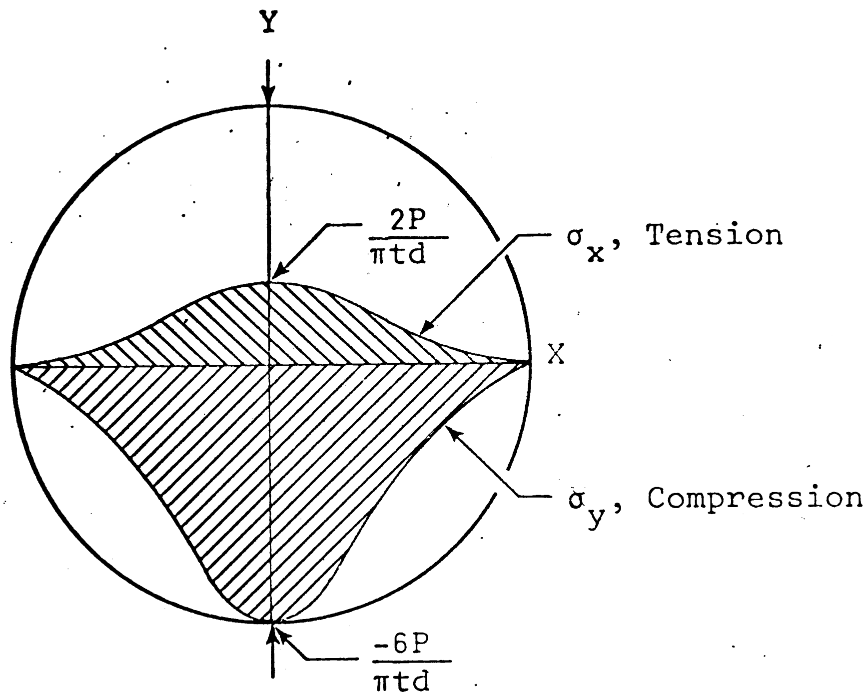

Figure 3. Stress distributions on x-axis. [1]

The stress distributions along the vertical y-axis through the use of equations 5 and 6 are shown in Figure 4. These equations can be simplified to be[1]

$$\sigma_x = \frac{2P}{\pi\ td} \tag{9}$$

$$\sigma_x = \frac{-2P}{\pi\ td}\left(\frac{2}{d-2y} + \frac{2}{d+2y} - \frac{1}{d}\right) \tag{10}$$

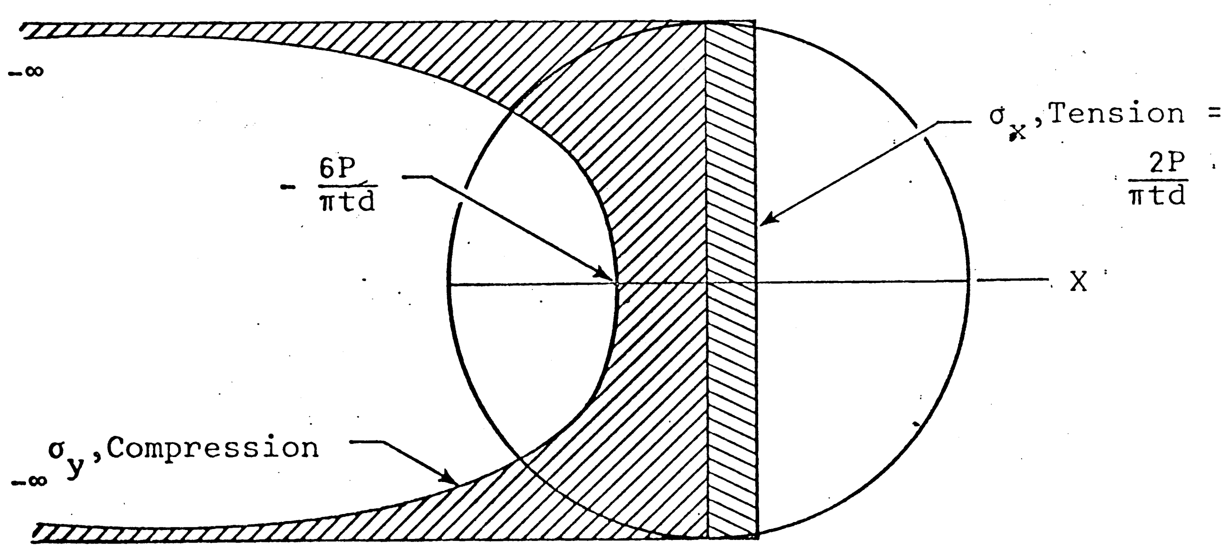

Figure 4. Stress distributions on y-axis. [1]

Variations from Theory

The theory which has been developed will give the exact solution for an idealized case. However, in testing asphalt theoretical conditions will never be attained. Assumptions that were made during the development of the theory are:[1]

1. Homogeneity of asphaltic concrete.
2. Hooke's law is valid for asphaltic concrete.
3. Point loading.

Since these assumptions are not valid for the indirect tensile test the variations have to be considered.

Bituminous materials are heterogeneous, which causes a less than ideal condition. The heterogeneity[1] of the material affects the stress distributions, however the degree to which they do so has not been determined. Tests which have been performed show that the heterogeneity of the material definitely affected the stress distributions, although it was to such a small degree that the test was considered satisfactory for use.

Frocht's theory considers the material to be linearly elastic. This is not true for bituminous materials tested at slow loading rates because they show a visco-elastic behavior. Heukelom and Klomp[4] stated that Van der Poel defined the stiffness modulus of a visco-elastic material as time and temperature dependent. This is shown in Figure 5, where asphalt was subjected to a slow loading rate and a fast loading rate.

When the asphalt is subjected to a slow loading rate, it behaves as a viscous material and flows under a constant load.[5] As the loading rate is increased, the material will become more elastic, and it becomes almost completely elastic at very fast loading rates.

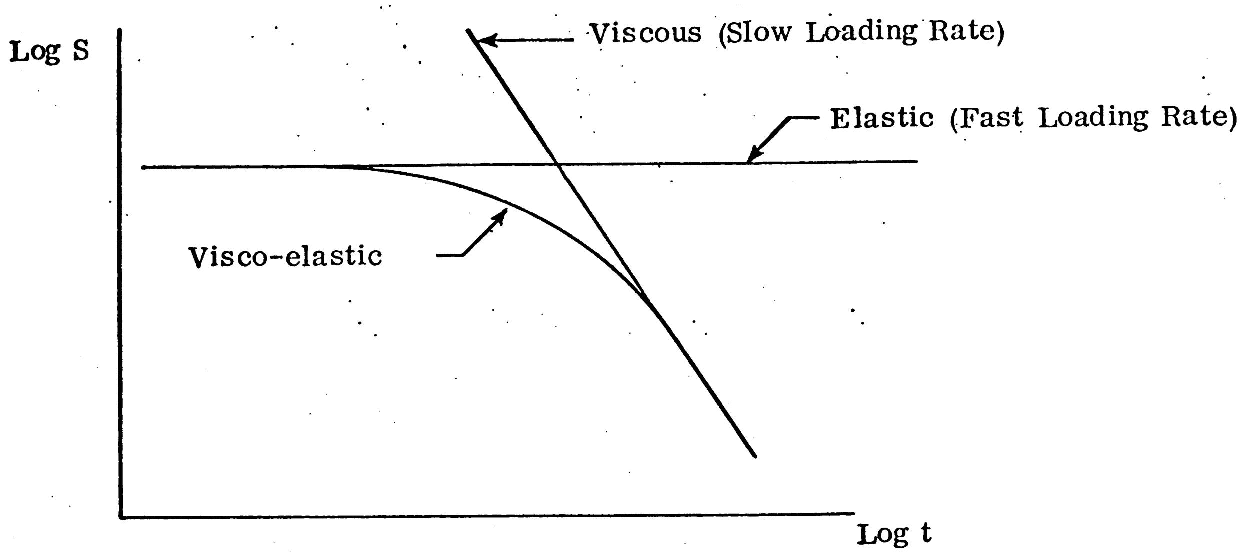

Figure 5. Stiffness modulus for asphalt as a function of the loading time. [4]

In static testing such as is usually done in the indirect tensile test, the modulus of elasticity increases with increased loading rates. The University of Texas[5] performed tests on asphalt specimens by varying the loading rates and recording the effect on the specimens. It was found that loading rates ranging from 0. 05 in. /min. (1.3 mm/min.) to 0.5 in. /min. (12.7 mm/min.) caused a fairly fast increase in the modulus of elasticity as the rate was increased. For rates of 0.5 in. /min. (12.7 mm/in.) up to 6 in. /min. (152.4 mm/min.), the modulus of elasticity increased at a much slower degree with an increased loading rate.

The development of the indirect tensile theory assumed that bituminous materials obey Hooke's law, that is, stress is proportional to strain. [1] However, this is not true because the modulus of elasticity will decrease with increased stress. Wright[6] felt that because of the nonelastic nature of the material, the more highly stressed parts of the specimen would be relieved by throwing the stress on elements where the stress was lower. This in turn would cause an increase in the load required to break the specimen. Hudson and Kennedy[1] felt that so long as the specimens failed in tension, the results obtained from the indirect tensile test were satisfactory for use. However, for less brittle materials, such as asphaltic concrete in a warm state, the test did not give satisfactory results because the specimen would fail in compression.

Frocht's theory also assumed that the loading was a point loading not spread evenly over a 1/2" (12.7 mm) wide loading strip as is the case in the indirect tensile test. The stress components that are developed by the loading strips are shown in Figure 6.

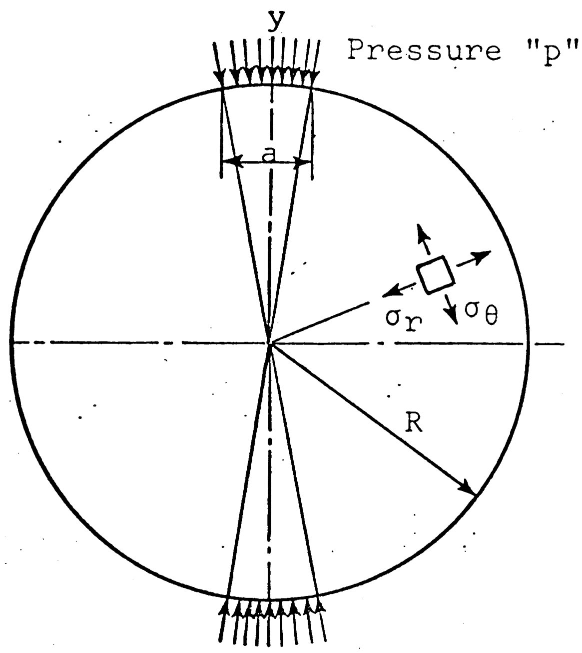

Figure 6. Stress components of specimen compressed using loading strips. [5]

Hondros[7] developed equations for the stresses along the principal diameters when using loading strips. It was found that the stress distributions did vary from those caused by a point loading; however, the stresses at center were the same for both point loading and with the loading strips. The stress distributions[5] produced when the loading heads are used are shown in Figure 7. It can be seen that the σ_y stress goes from tension in the center to compression as it approaches the loading strips. Hondros[7] states that the compressive stress along the y-axis is approximately twice that of the tensile stress. Therefore, since asphalt can withstand considerable more compressive stress than tensile stress, the specimen will fail in tension.

In a report published by Hadley, Hudson, and Kennedy,[8] the effects of varying the properties of bituminous concrete on the indirect tensile strength and modulus of elasticity were discussed. The values of tensile strength and modulus of elasticity were determined by using a regression analysis and varying the aggregate type, gradation, asphal cement type, asphalt content, and compaction temperature. The values are shown in Tables 1 through 4.

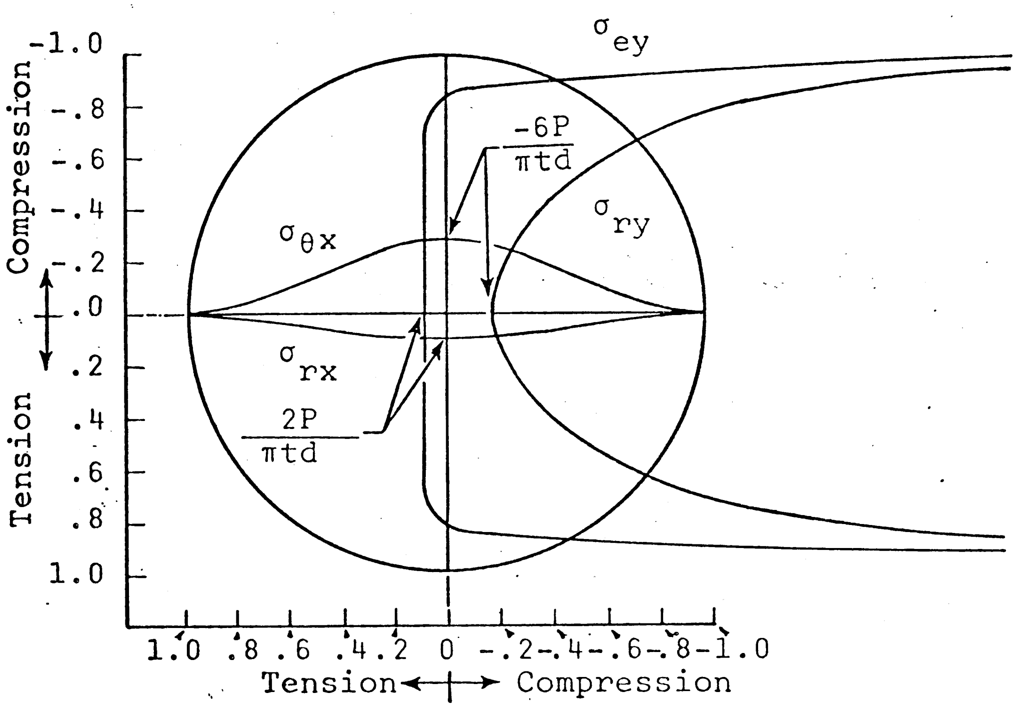

Figure 7. Stress distributions along principal axes when a 0.4" wide loading strip is used.[5]

Table 1

ESTIMATED INDIRECT TENSILE STRENGTHS FOR
ASPHALT-TREATED LIMESTONE MIXTURES
(From Reference 8)

Compaction Temperature °F	Asphalt Content, %	Fine AC-5	Fine AC-10	Fine AC-20	Medium AC-5	Medium AC-10	Medium AC-20	Coarse AC-5	Coarse AC-10	Coarse AC-20
200	4.	-	-	-	40.6	53.6	71.8	88.8	101.9	120.0
	4.5	2.3	15.3	33.5	66.0	79.0	97.2	103.5	116.5	134.7
	5.	32.7	45.7	63.9	85.7	98.7	116.9	112.4	125.4	143.6
	5.5	57.3	70.3	88.5	99.5	112.5	130.7	115.5	128.5	146.7
	6.	76.2	89.2	107.4	107.6	120.6	138.8	112.8	125.8	144.0
	6.5	89.2	102.2	120.4	109.9	122.9	141.1	104.4	117.4	135.6
	7.	96.5	109.5	127.7	106.4	119.5	137.6	90.2	103.2	121.4
	7.5	98.0	111.0	129.2	97.2	110.2	128.4	70.2	83.2	140.4
	8.	93.8	106.8	125.0	82.2	95.2	113.4	44.4	57.4	75.6
	8.5	83.8	96.8	115.0	61.4	74.5	92.6	12.9	25.9	44.1
	9.	68.0	81.0	99.2	34.9	47.9	66.1	-	-	6.8
	9.5	46.4	59.4	77.6	2.6	15.6	33.7	-	-	-
	10.	19.0	32.1	50.2	-	-	-	-	-	-
250	4.	-	-	10.5	69.3	82.3	100.5	133.2	146.2	164.4
	4.5	19.2	32.2	50.4	94.7	107.7	125.9	144.1	157.1	175.3
	5.	53.3	66.3	84.5	114.4	127.4	145.6	149.2	162.2	180.4
	5.5	81.7	94.7	112.9	128.2	141.2	159.4	148.6	161.6	179.8
	6.	104.2	117.3	135.4	136.3	149.3	167.5	142.1	155.2	173.3
	6.5	121.1	134.1	152.3	138.6	151.6	169.8	130.6	143.0	161.2
	7.	132.1	145.1	163.3	135.2	148.2	166.4	112.0	125.0	143.2
	7.5	137.4	150.4	168.6	125.9	138.9	157.1	88.3	101.3	119.5
	8.	136.9	149.9	168.1	110.9	123.9	142.1	58.8	71.8	90.0
	8.5	130.6	143.6	161.8	90.2	103.2	121.4	23.5	36.5	54.7
	9.	118.5	131.6	149.7	63.6	76.6	94.8	-	-	13.3
	9.5	100.7	113.7	131.9	31.3	44.3	62.5	-	-	-
	10.	77.1	90.2	108.3	-	6.2	24.4	-	-	-
300	4.	-	5.4	23.6	98.0	111.1	129.2	177.5	190.5	208.7
	4.5	36.0	49.0	67.2	123.4	136.5	154.6	184.7	197.7	215.9
	5.	73.9	86.9	105.1	143.1	156.1	174.3	186.0	199.1	217.2
	5.5	106.0	119.0	137.2	156.9	170.0	188.1	181.6	194.7	212.8
	6.	132.3	145.4	163.5	165.0	178.0	196.2	171.5	184.5	202.7
	6.5	152.9	165.9	184.1	167.3	180.4	198.5	155.5	168.6	186.7
	7.	167.7	180.7	198.9	163.9	176.9	195.1	133.8	146.8	165.0
	7.5	176.7	189.7	207.9	154.6	167.7	185.8	106.3	119.4	137.5
	8.	180.0	193.0	211.2	139.6	152.7	170.8	73.1	86.1	104.3
	8.5	177.4	190.5	208.6	118.9	131.9	150.1	34.1	47.1	65.3
	9.	169.1	182.2	200.3	92.3	105.3	123.5	-	2.3	20.5
	9.5	155.1	168.1	186.3	60.0	73.0	91.2	-	-	-
	10.	135.2	148.2	166.4	21.9	34.9	53.1	-	-	-

Present author's note — Basic conversion unit: 1 psi = 6894 Pa.

Table 2

ESTIMATED INDIRECT TENSILE STRENGTHS FOR ASPHALT-TREATED GRAVEL MIXTURES

(From Reference 8)

Compaction Temperature, °F	Asphalt Content, %	Fine AC-5	Fine AC-10	Fine AC-20	Medium AC-5	Medium AC-10	Medium AC-20	Coarse AC-5	Coarse AC-10	Coarse AC-20
200	4.	9.	22.1	40.2	40.6	53.6	71.8	46.0	59.0	77.2
	4.5	38.0	51.1	69.2	66.0	79.0	97.2	67.8	80.8	99.0
	5.	61.3	74.3	92.5	85.7	98.7	116.9	83.8	96.8	115.0
	5.5	78.7	91.8	109.9	99.5	112.5	130.7	94.1	107.1	125.3
	6.	90.4	103.5	121.6	107.6	120.6	138.8	98.5	111.5	129.7
	6.5	96.4	109.4	127.6	109.9	122.9	141.1	97.2	110.3	128.4
	7.	96.5	109.5	127.7	106.4	119.5	137.6	90.2	103.2	121.4
	7.5	90.9	103.9	122.1	97.2	110.2	128.4	77.3	90.3	108.5
	8.	79.5	92.5	110.7	82.2	95.2	113.4	58.7	71.7	89.9
	8.5	62.3	75.3	93.5	61.4	74.5	92.6	34.3	47.4	65.5
	9.	39.4	52.4	70.6	34.9	47.9	66.1	4.2	17.2	35.4
	9.5	10.7	23.7	41.9	2.6	15.6	33.7	-	-	-
	10.	-	-	7.4	-	-	-	-	-	-
250	4.	22.1	35.1	53.3	69.3	82.3	100.5	90.3	103.3	121.5
	4.5	54.9	67.9	86.1	94.7	107.7	125.9	108.4	121.4	139.6
	5.	81.9	94.9	113.1	114.4	127.4	145.6	120.6	133.6	151.8
	5.5	103.1	116.1	134.3	128.2	141.2	159.4	127.1	140.1	158.3
	6.	118.5	131.6	149.7	136.3	149.3	167.5	127.9	140.9	159.1
	6.5	128.2	141.2	159.4	138.6	151.6	169.8	122.8	135.8	154.0
	7.	132.1	145.1	163.3	135.2	148.2	166.4	112.0	125.0	143.2
	7.5	130.2	143.2	161.4	125.9	138.9	157.1	95.4	108.4	126.6
	8.	122.6	135.6	153.8	110.9	123.9	142.1	73.0	86.1	104.2
	8.5	109.2	122.2	140.4	90.2	103.2	121.4	44.9	57.9	76.1
	9.	90.0	103.0	134.2	63.6	76.6	94.8	11.0	24.0	42.2
	9.5	65.0	78.0	96.2	31.3	44.3	62.5	-	-	2.5
	10.	34.3	47.3	65.5	-	6.2	24.4	-	-	-
300	4.	35.2	48.2	66.4	98.0	111.1	129.2	134.6	147.7	165.8
	4.5	71.7	84.8	102.9	123.4	136.5	154.6	148.9	162.0	180.1
	5.	102.5	115.5	133.7	143.1	156.1	174.3	157.5	170.5	188.7
	5.5	127.4	140.5	158.6	156.9	170.0	188.1	160.2	173.2	191.4
	6.	146.6	159.7	177.8	165.0	178.0	196.2	157.2	170.2	188.4
	6.5	160.1	173.1	191.3	167.3	180.4	198.5	148.4	161.4	179.6
	7.	167.7	180.7	198.9	163.9	176.9	195.1	133.8	146.8	165.0
	7.5	169.6	182.6	200.8	154.6	167.7	185.8	113.5	126.5	144.7
	8.	165.7	178.7	196.9	139.6	152.7	170.8	87.4	100.4	118.6
	8.5	156.0	169.0	187.2	118.9	131.9	150.1	55.5	68.5	86.7
	9.	140.6	153.6	171.8	92.3	105.3	123.5	17.8	30.9	49.0
	9.5	119.4	132.4	150.6	60.0	73.0	91.2	-	-	5.6
	10.	92.4	105.4	123.6	21.9	34.9	53.1	-	-	-

Present author's note — Basic conversion unit: 1 psi = 6894 Pa.

Table 3

ESTIMATED MODULUS OF ELASTICITY VALUES FOR
ASPHALT-TREATED LIMESTONE MIXTURES
(From Reference 8)

Note: All values are in psi and must be multiplied by 10^5

Gradation		Fine			Medium			Coarse		
Compaction Temperature, °F	Asphalt Content, % / Asphalt Cement Type	AC-5	AC-10	AC-20	AC-5	AC-10	AC-20	AC-5	AC-10	AC-20
200	4.	-	-	0.322	1.401	1.732	2.194	2.485	2.816	3.278
	4.5	.300	.630	1.093	1.926	2.256	2.719	2.763	3.094	3.556
	5.	.942	1.272	1.735	2.322	2.652	3.115	2.913	3.243	3.706
	5.5	1.456	1.786	2.249	2.589	2.920	3.382	2.934	3.264	3.727
	6.	1.841	2.172	2.634	2.728	3.059	3.521	2.827	3.157	3.620
	6.5	2.098	2.428	2.891	2.739	3.069	3.532	2.591	2.921	3.384
	7.	2.226	2.557	3.019	2.621	2.951	3.414	2.226	2.557	3.019
	7.5	2.226	2.557	3.019	2.374	2.704	3.167	1.734	2.064	2.527
	8.	2.098	2.428	2.891	1.999	2.329	2.792	1.112	1.442	1.905
	8.5	1.840	2.171	2.633	1.496	1.826	2.289	0.362	.693	1.155
	9.	1.455	1.785	2.248	.864	1.194	1.657	-	-	.277
	9.5	.941	1.271	1.734	.103	.433	0.896	-	-	-
	10.	.298	0.628	1.091	-	-	-	-	-	-
250	4.	-	-	0.316	2.163	2.493	2.956	4.014	4.344	4.807
	4.5	.422	.752	1.215	2.687	3.018	3.480	4.164	4.494	4.957
	5.	1.192	1.522	1.985	3.083	3.414	3.876	4.186	4.516	4.979
	5.5	1.834	2.164	2.627	3.351	3.681	4.144	4.079	4.409	4.872
	6.	2.347	2.677	3.140	3.490	3.820	4.283	3.844	4.174	4.637
	6.5	2.732	3.062	3.525	3.500	3.830	4.293	3.480	3.810	4.273
	7.	2.988	3.318	3.781	3.382	3.712	4.175	2.988	3.318	3.781
	7.5	3.116	3.446	3.909	3.136	3.466	3.929	2.367	2.697	3.160
	8.	3.115	3.445	3.908	2.761	3.091	3.554	1.618	1.948	2.411
	8.5	2.985	3.316	3.778	2.257	2.587	3.050	0.740	1.070	1.533
	9.	2.728	3.058	3.521	1.625	1.955	2.418	-	.064	.527
	9.5	2.341	2.672	3.134	.865	1.195	1.658	-	-	-
	10.	1.826	2.157	2.619	-	.306	.669	-	-	-
300	4.	-	-	0.311	2.924	3.255	3.717	5.542	5.873	6.335
	4.5	.544	.875	1.337	3.449	3.779	4.242	5.565	5.895	6.358
	5.	1.442	1.773	2.235	3.845	4.175	4.638	5.459	5.789	6.252
	5.5	2.212	2.542	3.005	4.112	4.443	4.905	5.224	5.554	6.017
	6.	2.853	3.183	3.646	4.251	4.581	5.044	4.861	5.191	5.654
	6.5	3.365	3.696	4.158	4.262	4.592	5.055	4.369	4.700	5.162
	7.	3.749	4.080	4.542	4.144	4.474	4.937	3.749	4.080	4.542
	7.5	4.005	4.335	4.798	3.897	4.227	4.690	3.001	3.331	3.794
	8.	4.132	4.462	4.925	3.522	3.852	4.315	2.124	2.454	2.917
	8.5	4.130	4.461	4.923	3.019	3.349	3.812	1.118	1.448	1.911
	9.	4.000	4.331	4.793	2.387	2.717	3.180	-	.314	.777
	9.5	3.742	4.072	4.535	1.626	1.956	2.419	-	-	-
	10.	3.355	3.685	4.148	0.737	1.067	1.530	-	-	-

Present author's note — Basic conversion unit: 1 psi = 6894 Pa.

Table 4

ESTIMATED MODULUS OF ELASTICITY VALUES FOR ASPHALT-TREATED GRAVEL MIXTURES

(From Reference 8)

Note: All values are in psi and must be multiplied by 10^5

Compaction Temperature, °F	Asphalt Content, %	Fine AC-5	Fine AC-10	Fine AC-20	Medium AC-5	Medium AC-10	Medium AC-20	Coarse AC-5	Coarse AC-10	Coarse AC-20
200	4.	-	.263	.725	.906	1.236	1.699	1.091	1.421	1.884
	4.5	.554	.884	1.347	1.430	1.761	2.223	1.519	1.849	2.312
	5.	1.046	1.376	1.839	1.826	2.157	2.619	1.818	2.149	2.611
	5.5	1.410	1.740	2.203	2.094	2.424	2.887	1.989	2.319	2.782
	6.	1.645	1.976	2.438	2.233	2.563	3.026	2.032	2.362	2.825
	6.5	1.752	2.083	2.545	2.243	2.574	3.036	1.946	2.276	2.739
	7.	1.731	2.061	2.524	2.125	2.456	2.918	1.731	2.061	2.524
	7.5	1.581	1.911	2.374	1.879	2.209	2.672	1.388	1.718	2.181
	8.	1.302	1.633	2.095	1.504	1.834	2.297	.916	1.247	1.709
	8.5	.896	1.226	1.689	1.000	1.330	1.793	.316	.647	1.109
	9.	.360	.690	1.153	.368	.698	1.161	-	-	0.381
	9.5	-	.026	0.489	-	-	0.401	-	-	-
	10.	-	-	-	-	-	-	-	-	-
250	4.	-	.257	.720	1.667	1.998	2.460	2.619	2.950	3.412
	4.5	.676	1.006	1.469	2.192	2.522	2.985	2.919	3.250	3.712
	5.	1.296	1.626	2.089	2.588	2.918	3.381	3.091	3.421	3.884
	5.5	1.788	2.118	2.581	2.855	3.186	3.648	3.134	3.464	3.927
	6.	2.151	2.481	2.944	2.994	3.325	3.787	3.049	3.379	3.842
	6.5	2.386	2.716	3.179	3.005	3.335	3.798	2.835	3.165	3.628
	7.	2.492	2.823	3.285	2.887	3.217	3.680	2.492	2.823	3.285
	7.5	2.470	2.801	3.263	2.640	2.970	3.433	2.022	2.352	2.815
	8.	2.320	2.650	3.113	2.265	2.595	3.058	1.422	1.752	2.215
	8.5	2.040	2.371	2.833	1.762	2.092	2.555	.694	1.024	1.487
	9.	1.633	1.963	2.426	1.130	1.460	1.923	-	.168	0.631
	9.5	1.097	1.427	1.890	.369	.699	1.162	-	-	-
	10.	0.432	.762	1.225	-	-	0.273	-	-	-
300	4.	-	.252	.714	2.429	2.759	3.222	4.148	4.478	4.941
	4.5	.798	1.128	1.591	2.953	3.284	3.746	4.320	4.650	5.113
	5.	1.546	1.876	2.339	3.349	3.680	4.142	4.364	4.694	5.157
	5.5	2.166	2.496	2.959	3.617	3.947	4.410	4.279	4.609	5.072
	6.	2.657	2.987	3.450	3.756	4.086	4.549	4.066	4.396	4.859
	6.5	3.020	3.350	3.813	3.766	4.096	4.559	3.724	4.054	4.517
	7.	3.254	3.584	4.047	3.648	3.978	4.441	3.254	3.584	4.047
	7.5	3.360	3.690	4.153	3.402	3.732	4.195	2.655	2.985	3.448
	8.	3.337	3.667	4.130	3.027	3.357	3.820	1.928	2.258	2.721
	8.5	3.185	3.516	3.978	2.523	2.853	3.316	1.072	1.402	1.865
	9.	2.906	3.236	3.699	1.891	2.221	2.684	.088	.418	0.881
	9.5	2.497	2.828	3.290	1.131	1.461	1.924	-	-	-
	10.	1.961	2.291	2.754	.242	.572	1.035	-	-	-

Present author's note — Basic conversion unit: 1 psi = 6894 Pa.

The tensile strength of specimens using limestone aggregate was higher than that of the specimens using gravel. This can be explained by the fact that the limestone is more angular, has a rougher surface texture, and a greater porosity than the gravel, resulting in the better bond between the aggregate and the asphalt. The modulus of elasticity is also higher for the limestone mixture than for the gravel mixture.

The increasing of the compaction temperature led to increased values in the tensile strength and modulus of elasticity. The values for tensile strength and modulus of elasticity were also noticeably affected by the variations in asphalt cement type, as would be expected. These values increased as the asphalt cement type was changed from AC-5 to AC-10 to AC-20. Another notable fact is that the tensile strength and modulus of elasticity increased as the mix became coarser.

Each mix checked had an optimum asphalt content based on tensile strength, however, this value was affected by the gradation of the aggregate. For the fine materials the optimum asphalt content increased with increased compaction temperatures, whereas for the coarser materials the optimum asphalt content decreased as the compaction temperature increased. For the medium graded mixes the optimum asphalt content stayed nearly constant as the compaction temperature increased.

Equipment

The basic equipment[9] needed for performing the indirect tensile test is a loading apparatus capable of applying compressive loads at a desired deformation rate, the loading strips, and a means of measuring the applied load and the horizontal deformation of the specimen.

The loading apparatus[9] should be capable of applying enough compressive load to cause the specimen to fail and also capable of applying the load at a desired uniform rate. There is no standard loading rate, although the rates most used are 1-inch per minute

1734 (25 mm/min.) or 2-inches per minute (50 mm/min.), depending on the stiffness of the material. For stiffer materials, slower loading rates are used.

The loading strips[9] used are generally a half-inch wide with a curved face. When loading the specimen it is necessary to keep these strips as nearly parallel as possible so as to eliminate any bending stresses. A guided loading device as shown in Figure 8 is used to keep the loading strips parallel. This device has upper and lower plates to which the loading strips are fixed. The lower plate has two guide rods which allow the upper plate to slide vertically and remain parallel to the lower plate.

The applied load[10] can be measured by using a proving ring to indicate the compressive force if only the strength data are necessary. The compressive force and compressive deformation can be recorded for each test when using instrumentation similar to that used for Marshall stability and flow tests. If simultaneous load and deformation data are desired then a method of recording the load is necessary.

The horizontal deformation can be recorded by using two linear variable differential transformers[9] (LVDT) or a specially designed transducer[10] with strain gages mounted on cantilever aluminum arms. Strip-chart recorders should be used to record these measurements.

Test Procedure

The test procedure is listed below:[9]

1. "Determine the height and diameter of the test specimen.
2. Calibrate the horizontal deformation device.
3. Center test specimen on loading head.
4. Bring upper platen of die set into light contact with test specimen. Monitor load on the x-y platen that is recording load versus vertical deformation.
5. Place horizontal deformation device in position with arms in light contact with specimen and lock arms in position.
6. Load specimen at a constant deformation rate and record load, vertical deformation , and horizontal deformation."

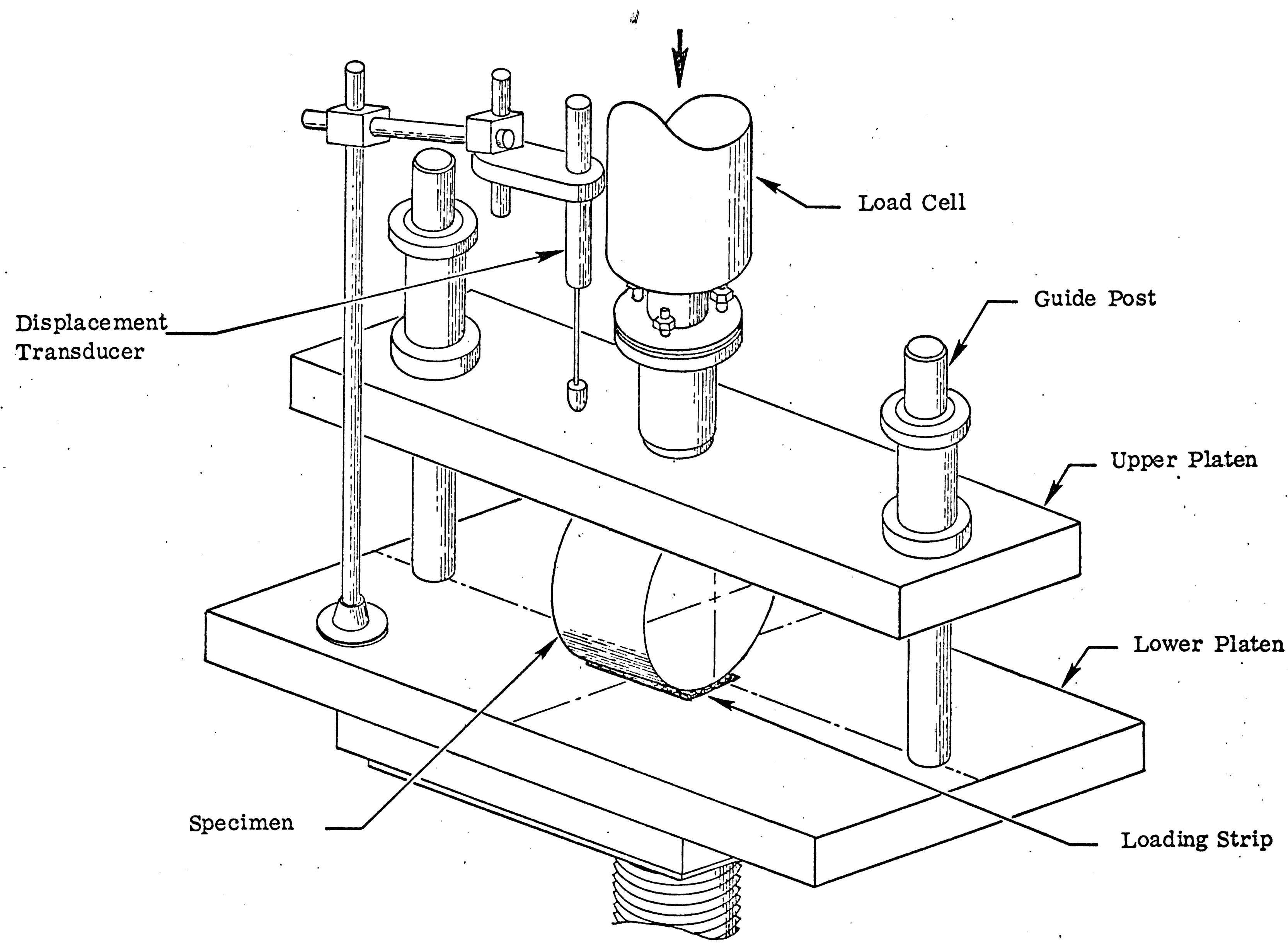

Figure 8. Loading head with rigid parallel platens. (9)

A Marshall specimen is used generally because its fabrication is quite simple and requires no special equipment.[10]

Determination of Tensile Strength, Poisson's Ratio and Modulus of Elasticity

The maximum tensile stress that occurs at the center of the specimen may be determined by equation 9, $\sigma_T = \frac{2P}{\pi td}$. For a 4-inch specimen this equation can be

$$\sigma_r = \frac{0.156\ P_{fail}}{t}$$

Poisson's ratio,[11] , is determined by the equation:

$$\nu = \frac{\int_{-r}^{r} \sigma_{ry} + R\int_{-r}^{r} \sigma_{rx}}{R\int_{-r}^{r} \sigma_{\theta x} + \int_{-r}^{r} \sigma_{\theta y}}$$

where: $\int_{-r}^{r} \sigma_{rx}$ and $\int_{-r}^{r} \sigma_{rx}$ = integration of radial stresses in the y and x directions, respectively

$\int_{-r}^{r} \sigma_{\theta x}$ and $\int_{-r}^{r} \sigma_{\theta y}$ = integration of radial stresses in the x and y directions, respectively

$R = \frac{y}{x}$ the least square line of best fit between the vertical deformation y and the corresponding horizontal deformation x up to the load P.

For a 4-inch (101.6 mm) specimen Poisson's ratio can be simplified to

$$\nu = \frac{0.0673R - 0.8954}{-0.2494R - 0.0156}$$

The modulus of elasticity, E, can be determined by

$$E = \frac{P}{x_T} \int_{-r}^{r} \frac{\sigma_{rx}}{P} \quad \nu \int_{-r}^{+r} \frac{\sigma_{\theta x}}{P}$$

where: $\frac{P}{x_T}$ = the least squares line of best fit between load P and the total horizontal deformation x for loads up to 50% of the load P_{max} at which the first break point occurs in the load deflection curve (see Figure 9).

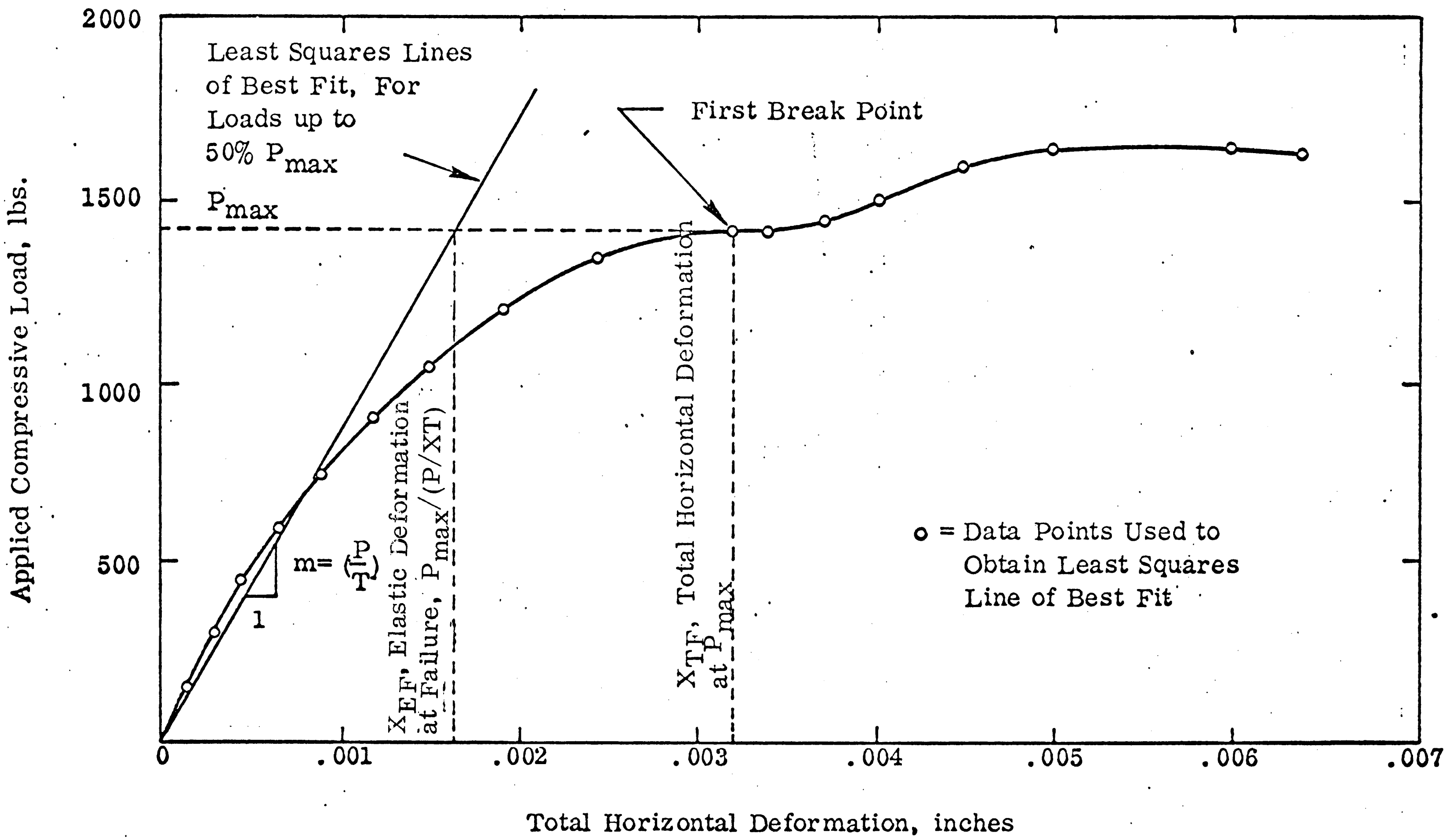

Figure 9: Generalized characterization of load-horizontal deformation data.[11]

$\int_{-r}^{+r} \frac{\sigma_{rx}}{P}$ and $\int_{-r}^{+r} \frac{\sigma_{\theta x}}{P}$ = the integration of the unit stresses σ_{rx} and σ_x.

When testing a 4-inch (101.6 mm) specimen the modulus of elasticity equation is reduced to

$$E = \frac{S_H}{t} \quad 0.9976\nu + 0.2692$$

where: S_H = horizontal tangent modulus $\frac{P}{X_t}$

Possible Correlation of Indirect Tensile Test Data to Fatigue Test Data

In a study performed by Maupin[10] of the Virginia Highway and Transportation Research Council, the work was focused on developing a correlation between the indirect tensile stiffness and the fatigue life of specimens tested under the constant strain mode.

Maupin used the data from the indirect tensile test to plot a typical stress-strain curve. This curve stayed linear until about three-quarters of the failure stress was reached, and thereafter the strain increased at a greater rate than did the stress. The stiffness value used by Maupin was the stiffness at three-quarters of the tensile failure stress, which is defined by $S_{3/4} = {}^{3/4}\ \sigma_{TF}/\varepsilon_{3/4}$

where: σ_{TF} = tensile stress at failure

$\varepsilon_{3/4}$ = tensile strain at three-quarters failure stress

The fatigue tests showed that stiffer mixes had shorter lives than flexible mixes when tested in the constant strain mode. Therefore by being able to determine the stiffness of the asphaltic concrete from an indirect tensile test it may be possible to determine fatigue life.

Marais[11] reported a tentative mix design of gap-graded bituminous surfacings whereby the indirect tensile strength is used as a criterion for fatigue design. A strong correlation was developed between the indirect tensile strength and the service life for several mixes. The tentative mix design limits the maximum indirect tensile strength at $40^{o}C$ ($104^{o}F$) to 680 kn/m^2 (99 psi). This work strongly supports the idea of using the indirect tensile test for fatigue design.

Resilient Modulus Indirect Tensile Test

A test method developed by Schmidt[12] of the Chevron Research Company uses a loading apparatus that is capable of applying a light pulsating load across the vertical diameter of a Marshall specimen. This load causes deformation across the horizontal diameter, which is measured by LVDT's.

The theory used in developing this test is the same as that used in the standard indirect tensile test, which uses a static loading. The major difference between the two tests is that Schmidt's test is nondestructive and obtains its resilient modulus by using a short duration dynamic load. The corresponding horizontal deformation caused by the vertical load can be recorded and thus the resilient modulus calculated. The equation used by Schmidt to determine the resilient modulus is

$$E = P\,(\nu + 0.2734)/t\,\Delta$$

where: P = dynamic load

ν = Poisson's ratio

t = thickness of specimen

Δ = total horizontal deformation

This equation for the resilient modulus is exactly the same as the one used for a static load, except for a minor deviation in the constants used.

The equipment used by Schmidt consists of an electrically activated solenoid, a pneumatic cylinder, a load cell, twin LVDT's, a recorder or readout, timing electronics and a frame for holding the specimen. The loading apparatus is the pneumatic cylinder which receives air pulses from an electrically activated solenoid. This pulse is applied every three seconds and is one-tenth of a second in duration.

Horizontal LVDT's are mounted to the specimen to measure its horizontal movement. This value is recorded on a strip recorder to correspond with the applied load.

Since Schmidt's dynamic loading better approximates fatigue test loading it could possibly offer a better correlation to fatigue life than the standard indirect tensile test. There has not been any attempt at such a correlation but it could possibly prove worth investigating.

Double Punch Test

The double punch test was first developed by W. F. Chen(13) as a method for determinating the tensile strength of concrete. Later Chen and Fang(14) expanded the use of the test to determine the tensile strength of cohesive soils. Through the work of Chen and Fang, Jimenez(15) decided the double punch test was a promising method for testing asphaltic concrete. The initial tests were done to measure stripping or debonding of asphalt from the aggregate.

The double punch test(15) is performed by centrally loading a cylindrical specimen on the top and bottom surfaces with cylindrical steel punches. A standard Marshall specimen will serve satisfactorily for the test. The loading by the punches causes cores to be developed in the specimen as shown in Figure 10. The penetration of the cores caused the specimen to split along the weakest radial plane.

The double punch test(15) has been compared to the indirect tensile test for repeatability and the relationship between the average stresses obtained for two aggregate gradations. The double punch proved to have better repeatability than the indirect tensile test and the average stresses obtained were nearly equal to those obtained from the indirect tensile test. Jimenez felt that the double punch test was simpler to perform and the stress analysis did not have to be adjusted for the area of the loaded surface.

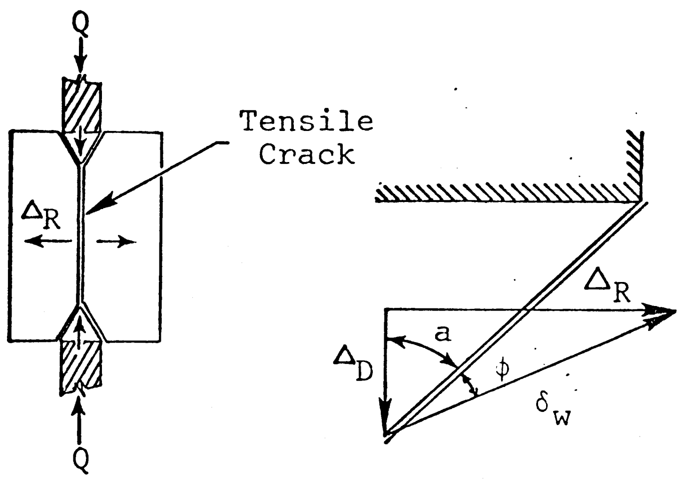

Figure 10. Bearing capacity of double punch test.[15]

The test is performed by centering the specimen in the bottom punch.[15] The punches are one-inch in diameter steel rods perfectly aligned one over the other. The upper punch is lowered until contact is made with the specimen. The specimen is then loaded at a rate of 1.0 inch per minute until failure.

The tensile strength[15] is computed by:

$$\sigma_T = \frac{P}{\pi(1.2\ bh - a^2)}$$

where: σ_T = tensile stress, psi (Pa)

P = maximum load, lb. (N)

a = radius of punch, in. (mm)

b = radius of specimen, in. (mm)

h = height of specimen, in. (mm)

Jimenez has developed a method of computing the modulus of elasticity. By using the measured values of mid-height radial displacements and vertical load and Table 5, the modulus of elasticity may be computed.

The double punch test is relatively new with regards to asphaltic concrete testing and no work has been reported on the effects of the various properties of the mix on the tensile strength or modulus of elasticity.

Cohesiometer Test

Another test used for finding tensile properties of asphalt is the cohesiometer test. It was developed by Hveem of the California Highway Department for use in designing asphaltic mixtures and pavements.(17)

The test is performed using a standard Marshall specimen (4" diameter x 2.5" height) (101.6 mm diam. x 63.5 mm height) which has been placed in the oven at 140°F for approximately two hours prior to testing.

The specimen is placed in the cohesiometer as shown in Figure 11. The cohesiometer is calibrated so that the lead shot used to load the specimen will flow into the shot receiver at a rate of 1800 ± 20 grams per minute. The thermostatically controlled heater is adjusted to maintain a $140^{\circ} \pm 2^{\circ}$ temperature in the cabinet. Once the specimen is clamped into position, the release pin is pulled to allow the shot to flow into the receiver. The shot is allowed to flow until the specimen breaks. However, if the specimen fails to break after the loading arm has moved 1/2-inch (12.7 mm) vertically, the loading will be stopped. The shot accumulated in the shot receiver is then weighed to the nearest gram and recorded as shot weight.

From the test described above, the cohesiometer value may be determined by

$$C = \frac{L}{W\,(.20H + 0.044H^2)}$$

Table 5

COEFFICIENTS FOR MODULUS OF ELASTICITY
BY U. OF A. DOUBLE PUNCH TEST*

Basic Conversion Unit: 1 in. = 2.54 cm

Poisson's Ratio = 0.35 and Punch Diameter = 1.00"

$$E_D = \frac{K\,P}{d}$$

E_D = Dynamic Modulus of Elasticity, psi

P = Repeated Vertical Load, lb.

d = Repeated Radial Displacement at Midheight, in.

K = Coefficient from Table below

Specimen Height, in.	Specimen Diameter, in.					
	3.0	3.2	3.4	3.6	3.8	4.0
1.5	.213	.210	.206	.201	.197	-
2.0	.235	.240	.243	.245	.245	.244
2.5	.218	.233	.245	.256	.264	.271
3.0	.181	.200	.219	.236	.252	.267
3.5	.139	.158	.179	.199	.219	.239
4.0	.100	.117	.137	.157	.178	.199
4.5	-	-	-	-	-	.157
5.0	-	-	-	-	-	.116

*Sent to authors by Jimenez, R. A.

1744 where: C = cohesiometer value (grams per inch (25.4 mm) width corrected to a 3-inch (76.2 mm) height)

L = weight of shot in grams

W = diameter of width of specimen in inches

H = height of specimen in inches

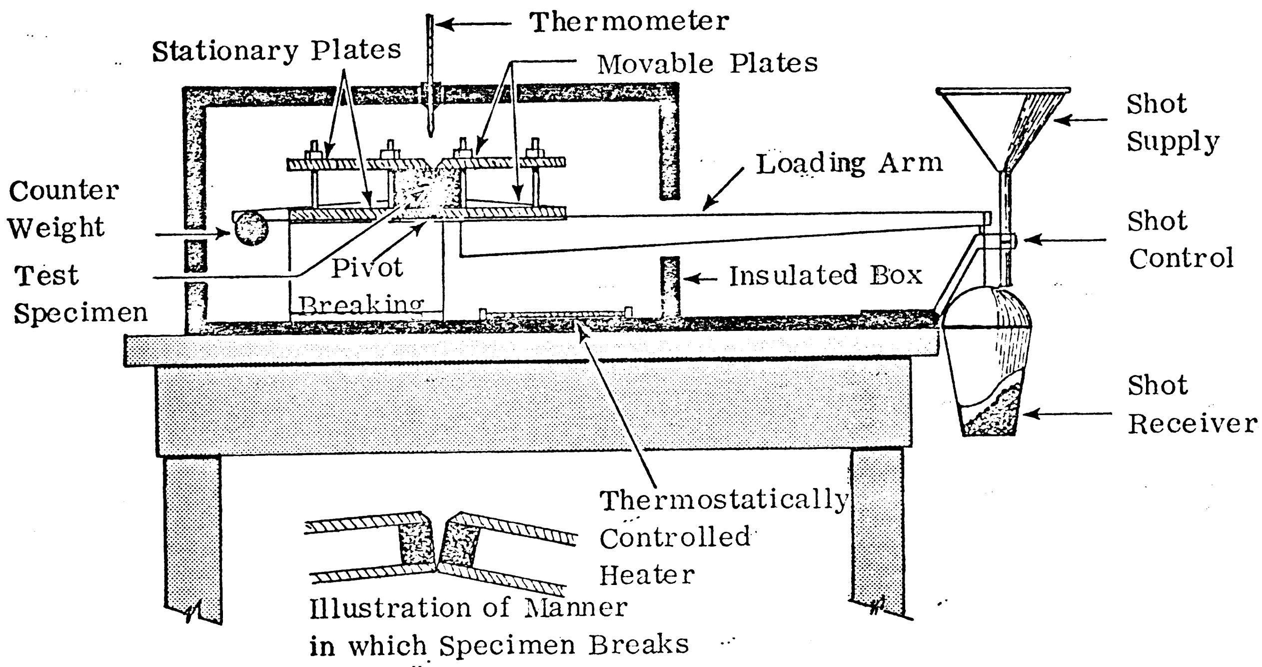

Figure 11. Diagrammatic sketch showing principal features of Hveem cohesiometer. (19)

In two experiments performed by Hadley, Hudson, and Kennedy, (19) the values from the indirect tensile test were compared to those of the cohesiometer test. The variables and design of the two experiments are shown in Figure 12.

The study was to establish whether a correlation existed between the modulus of elasticity, Poisson's ratio and tensile strength of the indirect tensile test, and the cohesiometer value by a linear regression analysis. The correlation of the variables was classified as:

1. No correlation,
2. a trend, and
3. an acceptable correlation.

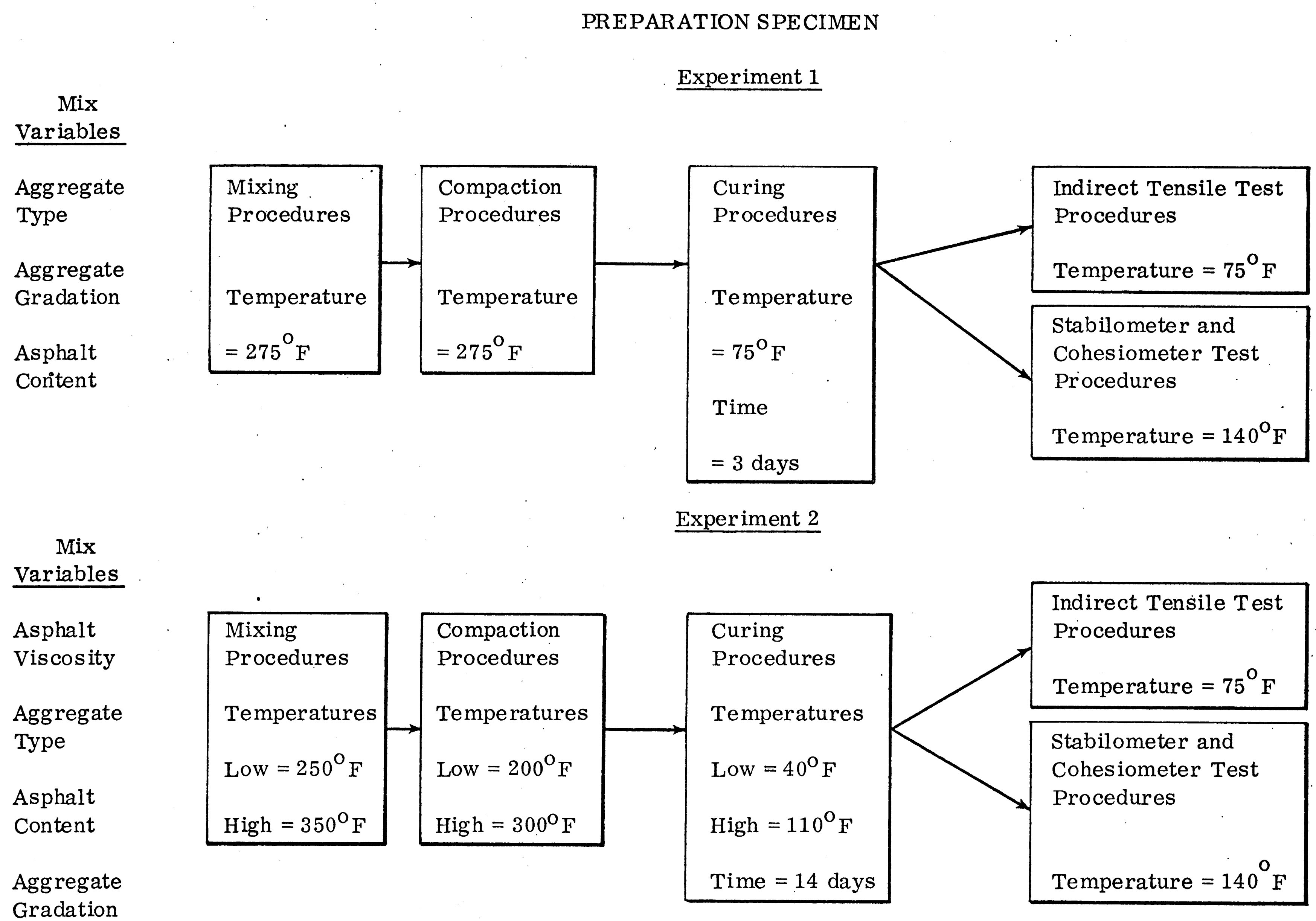

Figure 12. Experimental approach to correlation analysis.[19]

A relationship was classified as no correlation when the variables were independent of each other. A trend was described as a weak relationship between two variables with an increase in one variable resulting in a general increase or decrease in the other variable. An acceptable degree of correlation was given when one variable could be predicted from a second variable with a relatively high degree of reliability.

The results obtained from the experiments are shown in Table 6. It can be seen that when the results are combined no correlation exists between the Poisson's ratio and the cohesiometer value, but an acceptable correlation exists between the tensile strength and the cohesiometer value and the modulus of elasticity and the cohesiometer value.

It was generally felt that even though the predicted value for the modulus of elasticity was acceptable the test would not provide accurate values of Poisson's ratio that might be needed later.

Jimenez,[15] when searching for a simple tensile test for detecting the stripping or debonding of asphalt, stated that his prior experiences with the cohesiometer were not particularly good.

Hudson and Kennedy[1] do not recommend the test because of the nonuniform and undefined stress distribution which exists across the specimen and the fact that the maximum tensile stress occurs at the outer surface. This latter condition accentuates the effect of surface irregularities and may result in low indicated values of tensile strength.

Direct Tension

The direct tension test[1] is simple in theory and application. It is performed by applying a direct axial tensile force to a specimen and measuring the stress-strain characteristics of the material.

Table 6

PARAMETERS USED IN CORRELATION ANALYSIS FOR EXPERIMENT 1[19]

Variables	Correlation Coefficient r	Does Correlation Exist?	95% Confidence Bands About Correlation Coefficient	Slope Ratio	Coefficients of Variation, %	Acceptable Correlation?
Elasticity and cohesiometer value	.7238	Yes	$.356 \leq r \leq .898$	1.9	19, 13	Yes
Poisson's ratio and cohesiometer value	.4109	No				
Tensile strength and cohesiometer value	.6185	Yes	$.177 \leq r \leq .853$	2.6	15, 14	No
PARAMETERS USED IN CORRELATION ANALYSIS FOR EXPERIMENT 2[19]						
Elasticity and cohesiometer value	.8069	Yes	$.593 \leq r \leq .905$	1.5	29, 26	Yes
Poisson's ratio and cohesiometer value	-.6411	Yes	$-.337 \leq r \leq .824$	2.4	57, 34	No
Tensile strength and cohesiometer value	.8580	Yes	$.705 \leq r \leq .935$	1.4	21, 23	Yes

The results[20] are recorded by measuring the tensile force and the corresponding deformation of the specimen due to that force. The deformation can be measured by using dual LVDT's connected to a recorder. From this test the tensile strength and maximum elongation of the specimen can be computed. An important item to note is that the axis of failure must be outside of the elongation measuring area or the recorded elongation would be far too high.

The problems that arise with this test lie with the caliber of equipment needed to obtain satisfactory test results. One of the basic requirements in choosing a simple test method is that the method be simple and that the equipment can be purchased at relatively little cost.

When attempting to use relatively inexpensive test equipment, severe difficulties arise. The first problem is the gripping of the specimen, in which there are only two effective methods: one for a cylindrical specimen[1] and the other for a rectangular specimen.[21]

The cylindrical specimen[1] is gripped by cementing a semicircular loading head to the outer circumference of the specimen, as shown in Figure 13. This method reduces the effect of planes of weakness caused by compaction by layers, and also is convenient.

The rectangular specimen,[21] a 1.5" x 1.5" x 4.5" (38.1 mm x 38.1 mm x 114.3 mm) beam, is fastened with epoxy to the loading heads of the test system. This method also reduces the possibility of failure on a weak plane caused by the compaction by layers.

The test[21] is performed with the assumption that only pure tension is applied to the specimen. However any misalignments of the loading heads will introduce bending stresses and cause errors in the test results. The application of a pure tensile force is very difficult and time-consuming.

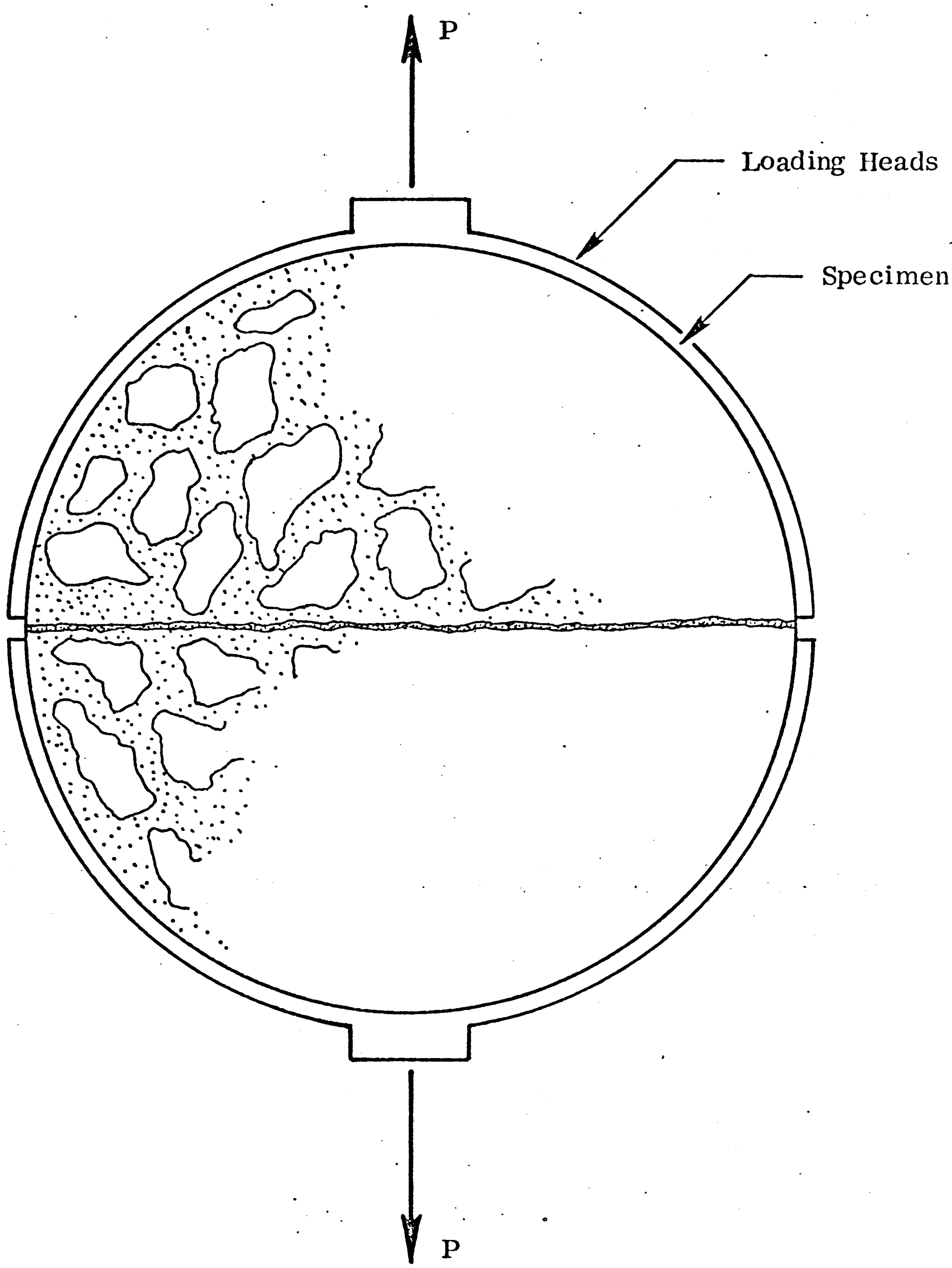

Figure 13. Diametrical direct tensile test. (1)

The use of good testing equipment helps to alleviate this problem to a certain degree. A testing system[21] which uses a universal joint for each loading head is shown in Figure 14. Epps and Monismith used an electro-hydraulic closed loop testing system capable of applying a constant rate of deformation.

Another problem that is encountered with the direct tensile test is the evaluation of the test results. It is normally assumed by engineers that the stress is uniformly distributed across the central cross section. However a report by Mitchell[22] states that the maximum stress on the central cross sectional plane was about 1.75 times larger than the average stress.

Hudson and Kennedy[1] state that "In view of these difficulties and uncertainties it is felt that the direct tensile test has limited application and that the test results obtained by this method are questionable."

Flexural Beam Test

The flexural beam test[1] is simple to perform. It is preferred by some engineers because of its similarity to the field loading of a pavement. This test, like the cohesiometer test, can be characterized as being more of a bending test than a tensile test. The beam is loaded one of two ways; the load is applied in two equal concentrated loads on third points of the beam, or it is applied as one concentrated force at the midpoint of the beam.

The beam[23] is tested by placing it in a frame with the ends simply supported and loading it using a constant rate of deformation. The load, P, and the deflection, Δf, of the beam can be obtained directly from the test.

The tensile strength of the beam can be found by using the equation

$$S_R = \frac{Mc}{I}$$

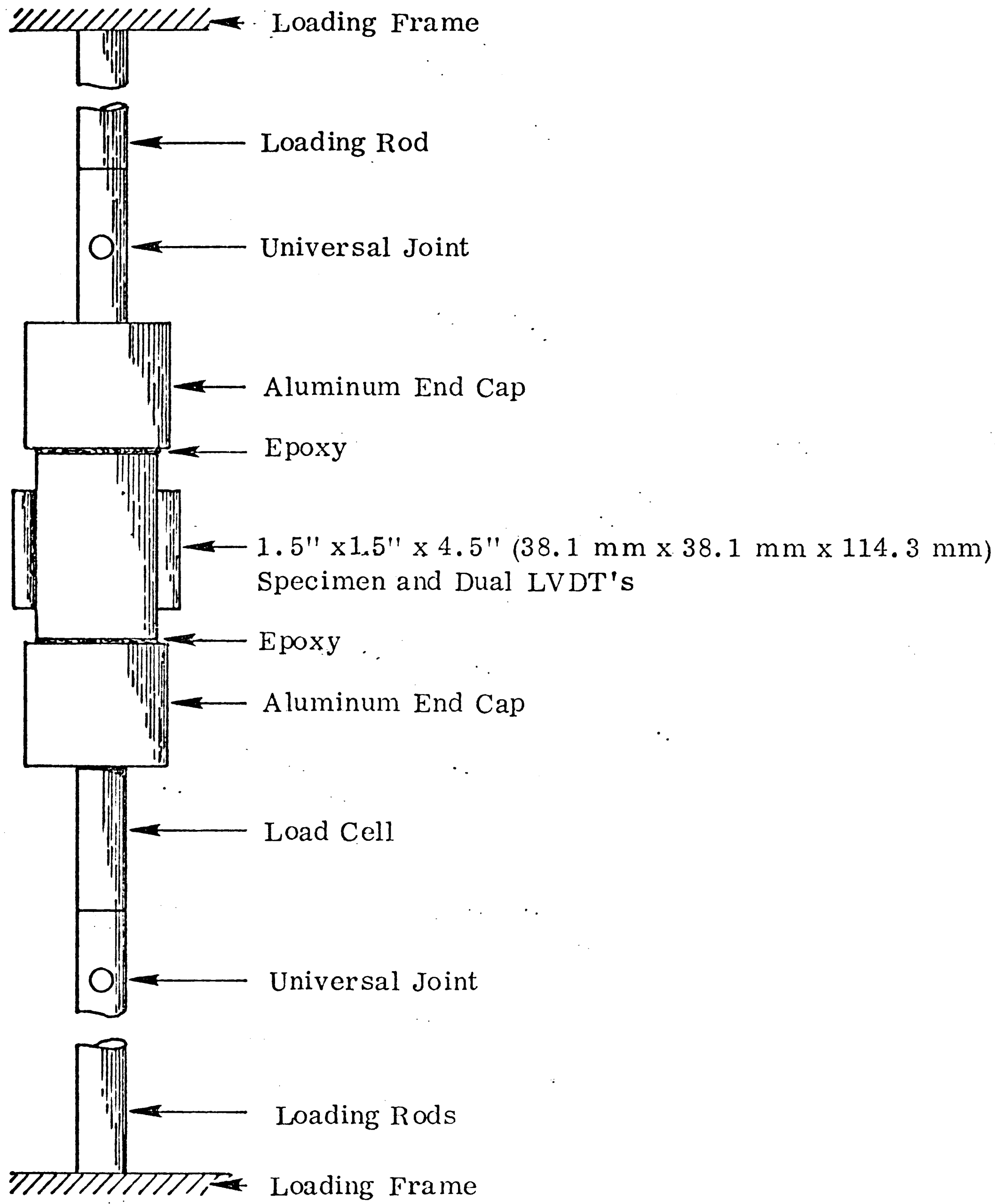

Figure 14. Direct tension testing apparatus.[23]

1752

where: M = moment in inch pounds (Nm)

c = one-half depth of the beam in inches (m)

I = moment of inertia in inches^4 (m^4)

This formula[1] assumes that the stress is proportional to the distance from the neutral axis, which means there is a linear stress-strain relationship in the tested material. This relationship is not valid for asphalt and is very much in error at failure. The use of this formula will usually give a higher tensile strength at failure than the actual strength.

Using the values of load and deflection from the test, the modulus of elasticity, often called the stiffness modulus, S_f, can be determined:[23]

$$S_f = \frac{\Delta P L^3}{48\, \Delta f I}$$

where: ΔP = change in load applied in lbs. (N)

L = span in inches (mm)

Δ f = deflection corresponding to P in inches (mm)

I = moment of inertia in inches.^{4} (mm^4)

In flexural beam tests performed by Bushy and Rader,[23] asphalts of three different penetration grades, 200/300, 85/100, and 40/50, were tested at a temperature of +25°F. The stiffness moduli for the different grades had coefficients of variation of 13.0%, 23.1%, and 21.5%, respectively. The coefficient of variation could be expected to increase when higher testing temperatures are used.

Hudson and Kennedy[1] felt that the flexural beam test had the same shortcomings that the cohesiometer test had. The major criticisms, as discussed earlier in the cohesiometer test, are the nonuniform and undefined stress distributions that occur during loading and the fact that the maximum tensile stress occurs at the outer surface where surface irregularities affect results.

Fatigue Prediction by Sonic Method

Freeme and Marias[24] revealed a correlation between bulk modulus as determined by ultrasonic sound wave measurements and the K value that appears in the fatigue equation, $N_f = K\ (1/\varepsilon)^n$, for constant strain fatigue tests (see Figure 15). Their work indicates a possibility of using ultrasonic methods to predict the fatigue life of bituminous mixtures.

Although ultrasonic equipment is not generally available, many agencies use a sonic device which is commercially available at reasonable cost to obtain freeze-thaw data on portland cement concrete specimens. Leslie and Cheesman[25] found a good correlation between the sonic moduli and the ultrasonic moduli (bulk modulus) for 300 concrete beams; therefore, it may be possible to use the sonic device to predict K for bituminous mixtures.

SUMMARY AND EVALUATION OF TEST METHODS

Table 7 lists and rates the simple test methods according to their prospective usefulness in predicting the fatigue of asphaltic concrete mixtures. The methods were rated according to the following:

1. Simplicity of sample preparation and testing equipment — Can the method utilize specimens that are currently used in design procedures and, if not, will new sample preparation and testing techniques be simple? An ideal specimen would be a cylindrical specimen, such as Marshall and Hveem, which is used in the other design procedures. Also the cylindrical specimen can be obtained from the pavement with simple coring equipment.

   Testing equipment should be relatively inexpensive and easy to operate so that tests could be performed in conventional mix design laboratories. If the equipment is expensive and requires extensive training for personnel it is very unlikely that it could be used on a routine basis for mix design.

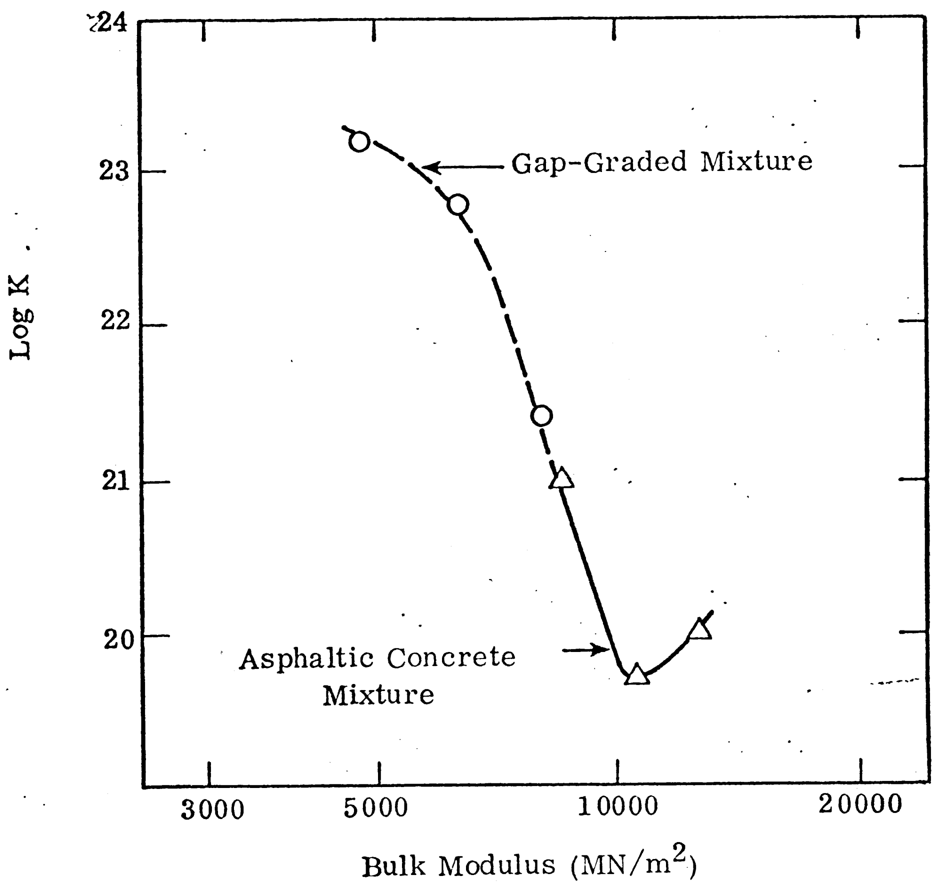

Figure 15. Variation of log K with bulk modulus.

Table 7

RATING SIMPLE TEST METHODS

Test	Simplicity of Sample Preparation and Test Equipment	Yield Accurate Desirable Information (stress, strain, modulus)	Correlated with Fatigue	Average Rating
Static Indirect Tensile Test	9	8	8	8.3
Resilient Modulus Test	8	8	-	8.0
Double Punch Test	9	8	-	8.5
Cohesiometer Test	9	4	-	6.5
Direct Tension Test	4	9	-	6.5
Flexure Test	7	7	-	7.0
Sonic Test	8	6	8	7.3

Rating scale: 0- least desirable 10- most desirable.

1756

2. Accurate desirable information — Although it is now known exactly what type of information is necessary to predict fatigue behavior, investigations have alluded to the type of data that may be useful. It has been shown that fatigue is related to stiffness, therefore a stiffness or modulus measurement may prove useful. Marais proposes using strength or stress criteria to control fatigue behavior, therefore, this measurement may be useful. Strain measurement would possibly be another useful item.

   Not only must the test method yield desirable information but the data must be accurate and not excessively variable.

   Recently developed pavement design procedures require the moduli of the individual pavement layers, therefore, if the asphalt modulus could be obtained from the same test it would be an additional benefit.

3. Correlation with fatigue — Since the correlation of a simple test with fatigue characteristics is the object of this project it is obvious there has not been a great deal of work in this area. However, there have been several studies that yielded correlations of fatigue and simple test results. These studies were mentioned previously.

   If a test has already been correlated with fatigue to some degree this is certainly in its favor.

The sensitivity of the test methods to testing conditions and mixture characteristics was surveyed. The static indirect tensile test, resilient modulus test, cohesiometer test, and direct tension test were found to be sensitive to most of the desired factors.

The other test methods have not been researched as extensively, therefore, not as much information is available on their sensitivity.

According to Table 7 the rating would be:

1. Double Punch
2. Static Indirect Tensile
3. Resilient Modulus
4. Sonic
5. Flexure
6. Direct Tension
7. Cohesiometer

It was proposed that four simple test methods would be selected for laboratory testing. The sonic test was added at the last moment because it can be performed on the fatigue specimens, and thus, no additional specimens need to be fabricated. Therefore, the simple test methods proposed for laboratory study are the double punch, static indirect tensile, resilient modulus, flexure and sonic.

REFERENCES

1. Hudson, W. Ronald, and Thomas W. Kennedy, "An Indirect Tensile Test for Stabilized Materials," Center for Highway Research, University of Texas at Austin, January 1968.

2. Timoshenko, S., and J. N. Goodier, "Stresses in a Circular Disk," Theory of Elasticity, Second Edition, McGraw-Hill, New York, N. Y., 1951, pp. 107-111.

3. Frocht, M. M., "Stresses in Circular Disks," Photoelasticity, Volume II, John Wiley and Sons, Inc., New York, N. Y., 1948, pp. 118-133.

4. Heukelem, W., and A. J. G. Klomp, "Road Design and Dynamic Loading," Proceedings, Association of Asphalt Paving Technologists, Vol. 33, February 1964, pp. 92-125.

5. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "An Evaluation of Factors Affecting the Tensile Properties of Asphalt-Treated Materials," Center for Highway Research, University of Texas at Austin, March 1969.

6. Wright, P. J. F., "Comments on an Indirect Tensile Test on Concrete Cylinders," Magazine of Concrete Research, London, March 1956.

7. Hondros, G., "The Evaluation of Poisson's Ratio and Modulus of Materials of a Low Tensile Resistance by the Indirect Tensile Test," Australian Journal of Applied Science, Vol. 10, No. 3.

8. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "Evaluation and Prediction of the Tensile Properties of Asphalt-Treated Materials," Center for Highway Research, University of Texas at Austin, May 1971.

9. Anagnos, James N., and Thomas W. Kennedy, "Practical Method of Conducting the Indirect Tensile Test," Center of Highway Research, University of Texas at Austin, August 1972.

10. Maupin, G. W. Jr., "Results of Indirect Tensile Tests Related to Asphalt Fatigue," Virginia Highway and Transportation Research Council, November 1971.

11. Marais, C. P., "Tentative Mix Design Criteria for Gap-Graded Bituminous Surfacings," National Institute for Road Research, Pretoria, South Africa, January 1974.

12. Schmidt, R. J., "A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes," Highway Research Record 404, 1972, pp. 22-32.

13. Chen, W. F., "Double Punch Test for Tensile Strength of Concrete," American Concrete Institute, Vol. 67, December 1970, pp. 993-995.

14. Fang, H. Y., and W. F. Chen, "New Method for Determination of Tensile Strength of Soils, Highway Research Record 345, 1971, pp. 62-68.

15. Jimenez, R. A., "Testing for Debonding of Asphalt from Aggregates,"Report to Arizona Highway Department, Research Project-Arizona HRP-1-10 (123), University of Arizona, April 1973.

16. Chen, W. F., "Extensibility of Concrete and Theorems of Limit Analysis," Journal of the Engineering Mechanics Division, ASCE, June 1970, pp. 341-352.

17. Jimenez, R. A., "Evaluation of the Cohesiometer Test for Asphalt Concrete," Highway Research Record 51, 1964, pp. 44-56.

18. Mix Design Methods for Asphaltic Concrete, The Asphalt Institute, Third Edition, October 1969.

19. Hadley, William O., W. Ronald Hudson, and Thomas W. Kennedy, "Correlation of Tensile Properties and Cohesiometer Values of Asphalt Treated Materials," Center of Highway Research, University of Texas at Austin, June 1970.

20. Guericke, R., and F. Weinert, "The Behavior of Bituminous Mixtures in Laboratory Tests and under Road Conditions," The University of Michigan Third International Conference on the Structural Design of Asphalt Pavements, London, England, September 1972, pp. 233-240.

21. Epps, Jon A., and Carl L. Monismith, "Influence of Mixture Variables on the Direct Tensile Properties of Asphalt," Proceedings, Association of Asphalt Paving Technologists, Vol. 39, February 1970, pp. 207-241.

22. Mitchell, W. B., Jr., "The Indirect Tension Test for Concrete," Materials Research and Standards, American Society for Testing Materials, Vol. 1, No. 10, October 1961, pp. 780-787.

23. Busby, Edward O., and Lloyd F. Rader, "Flexural Properties of Asphalt Concrete at Low Temperatures," Proceedings, Association of Asphalt Paving Technologists, Vol. 41, February 1972, pp. 163-187.

24. Freeme, Charles R., and Claude P. Marais, "Thin Bituminous Surfaces: Their Fatigue Behavior and Prediction," Special Report 140, Highway Research Board, 1973.

25. Leslie, J. R., and W. J. Chusman, "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures," American Concrete Institute Journal, Vol. 46, September 1949.