Use of Marshall Stability Test in Asphalt Paving Mix Design

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A continuing problem in the design of bituminous pavements is the specification of the properties of the mix so that it will have sufficient stability to resist displacement under traffic. This problem has been made more acute by the demands of heavier wheel loads which are anticipated for modern highways and airfields. Thus, to aid mix formulation there is a pressing need for specifications in terms of the results of laboratory tests.

An analysis of the Marshall Stability test shows that the bearing capacity of a paving mix can be related to Marshall Stability and flow by the following equation:

$$\text{Bearing Capacity (psi)} = 1/5\ \frac{\text{Stability}}{\text{Flow}} \times (2+K)\,F$$

in which

$$K = \frac{1 + \sin\phi}{1 - \sin\phi}$$

$$F = (1-0.055\,K)$$

Derivation of this equation is based on two important assumptions:

1. Allowable design stress corresponds to the stress calculated at 1 percent strain in the Marshall test.
2. Confining pressure in the pavement is equal to 50 percent of unconfined compressive strength (confinement is proportional to lateral strain; this is 50 percent of vertical strain for materials that do not change volume).

A convenient approximation of the above equation is given by:

$$\text{Bearing Capacity (psi)} = \frac{\text{Stability}}{\text{Flow}}\ \frac{(120-\text{Flow})}{100}$$

The design curves representing the above relationships emphasize that the load-carrying ability of an asphaltic mix is a function of the flow value as well as the stability and reveal the inadequacy of the usual specifications which call for only a minimum stability and maximum flow value. A single bearing capacity for any mix can be calculated from the combination of stability and flow. Marshall Stability alone, however, is not an absolute measure of strength.

It is believed that the results of this analysis will be very useful in highway and airfield design.

●THERE ARE several tests commonly employed at the present time to measure the resistance to deformation of asphalt-aggregate mixtures (1). These tests include:

1. Marshall Stability
2. Hveem Stabilometer
3. Hubbard-Field
4. Unconfined Compression
5. Triaxial

All of these are used to measure plastic stability or the ability of a mix to resist being squeezed out from under a load. All except the triaxial and possibly the unconfined compression tests are empirical and are not considered to measure any fundamental material property. They are extensively used, however, in design and control work.

Popularity of these tests can be divided somewhat according to geographical location, but the most widely used at present is the Marshall Stability test (2), originally developed by the U.S. Army, Corps of Engineers (3). Because of its wide usage it is the basis of many specifications and is a familiar and accepted measure of stability. Quite often design problems must be solved by this test alone. Thus, it is essential to obtain a better understanding of its significance.

During the study of a number of small-scale pavement test sections, however, it became especially evident that neither Marshall Stability nor flow value alone satisfactorily predicted resistance to plastic displacement. It appeared that sections having equal stabilities did not have the same supporting power when their flow values differed. Similarly, sections having equal flow values often performed quite differently as a result of differences in stability. Examples are shown in the following table.

MIXES OF EQUAL STABILITY

Section No.	Stability (lb)	Flow Value (0.01 in.)	Performance (Resistance to Plastic Displacement)
3A-7B	1460	6	Satisfactory
2B-11B	1425	12	"
2A-2B	1400	13	Plastic
2B-15A	1465	16	"
2B-2B	1425	16	"
	MIXES OF EQUAL FLOW VALUE		
3A-4B	4005	13	Satisfactory
2A-17B	2010	13	"
2A-2B	1400	13	Plastic
2A-5B	1170	13	"

Because of these problems and of the need to make a satisfactory appraisal of the properties of the field test sections, it was decided to make a closer investigation of the Marshall test which could serve as a basis for interpretation. To make better use of the test it appeared necessary to answer two fundamental questions: (a) What material properties are being measured in the Marshall test? (b) What is the relation of these properties to the bearing capacity of a paving mix?

INTERPRETATION OF MARSHALL STABILITY RESULTS

A review of the literature shows that only a limited amount of work has been done to define the properties measured in the Marshall test. A previous investigation by Fink and Lettier (4) has shown the influence of asphalt viscosity on stability values and Endersby and Vallerga (5) have demonstrated the effects of different compaction methods on test results. Van Iterson (6) interpreted the loading of a cylindrical shape such as used in the Marshall test as being similar to an unconfined compression test. Goetz and McLaughlin (7, 8) have made some of the few studies that attempted to examine the results of Marshall testing in the light of triaxial and unconfined compression tests. A conclusion from their work is that the Marshall test is a type of confined test in which the confinement is attributed to the curved shape of the testing heads. Their work is significant because identical materials were tested in both the Marshall test and the unconfined compression test. The method of specimen preparation was not a variable in the comparison.

Use of the test for design purposes has indicated that a type of shear failure occurs in the test (Figure 1) that is similar to failures in direct compression tests.

Analysis of the forces involved in the Marshall test shows that the measured vertical force is the sum of the stresses acting on the curved surface of the testing head at the interface with the specimen. These stresses consist of normal (S_n) and tangential (S_s) components as shown in Figure 2. For any small elemental area dA on the testing head, the vertical stress S_v is given by:

$$S_v \cos\alpha \; dA = S_n \cos\alpha \; dA + S_s \sin\alpha \; dA \qquad (1)$$

substituting

$$dA = rt \, d\alpha$$

where

r = radius of curved surface
t = width of area (normal to plane surface of specimen)

produces

$$rt \, S_v \cos\alpha \; d\alpha = rt \, S_n \cos\alpha \; d\alpha + rt \, S_s \sin\alpha \; d\alpha \qquad (2)$$

Then, since α ranges from 0 to ± 70 in the Marshall apparatus, the sum of all the vertical forces acting on the head becomes

$$2\int_{\alpha=0}^{\alpha=70^0} rt \, S_v \cos\alpha \; d\alpha = 2\int_{\alpha=0}^{\alpha=70^0} rt \, S_n \cos\alpha \; d\alpha + 2\int_{\alpha=0}^{\alpha=70^0} rt \, S_s \sin\alpha \, d\alpha \qquad (3)$$

Deformation of the specimen normal to the testing head is approximately equal to $y_o \cos\alpha$ where y_o is the vertical deformation of the specimen at the center. If stress is taken to be proportional to deformation, then the normal stress at any point on the testing head is $S_n = S_o \cos\alpha$, in which S_o is the vertical stress at the center of the test head. Substituting this in Eq. 3, the total vertical reaction force R in the Marshall test is given by the value of the integral.

$$2\int_{\alpha=0}^{\alpha=70^0} rt \, S_v \cos\alpha \; d\alpha = R = 2\int_{\alpha=0}^{\alpha=70^0} rt \, S_o \cos^2\alpha \, d\alpha + 2\int_{\alpha=0}^{\alpha=70^0} rt \, S_s \sin\alpha \, d\alpha \qquad (4)$$

If the tangential or shearing stresses are developed by friction alone,

$$S_s = f \, S_n = f \, S_o \cos\alpha$$

The expression for vertical reaction then becomes

$$R = 2\,rt\int_{\alpha=0}^{\alpha=70^0} (S_o \cos^2\alpha + S_o \sin\alpha \cos\alpha) \, d\alpha \qquad (5)$$

Evaluation of the integral produces

$$R = (1.54 + 0.88\,f) \; rt \, S_o \qquad (6)$$

For values of the coefficient of friction in the range of 0.4 to 0.6, Eq. 6 is approximately equal to: $R = 2 \, rt \, S_o$

For the Marshall test, r = 2 in., t = 2.5 in., so using English units,

$$R = 10 \, S_o \qquad (7)$$

Coefficients of static friction of 0.4 to 0.5 have been measured in the laboratory and thus Eq. 7 seems a fair representation of stress conditions in the Marshall test.

If, then, the Marshall test is a type of unconfined compression test, Marshall Stability should be approximately ten times the unconfined compressive stress. The investigations of McLaughlin and Goetz (8), however, have demonstrated that Marshall Stabilities are much greater than this amount. Thus, the Marshall test resembles a compression test performed on a specimen of low height to diameter ratio in which the

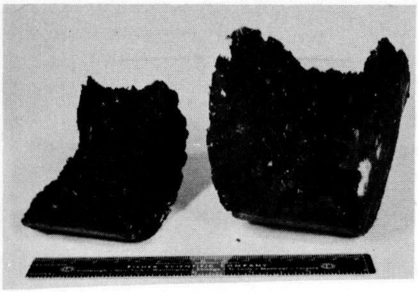

Figure 1. Shear planes developed in Marshall Test specimen.

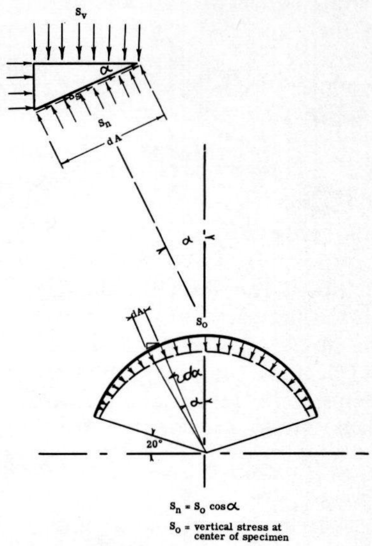

Figure 2. Stress relations in Marshall Stability test.

failure planes intersect the testing head. Such an arrangement is represented by the drawing in Figure 3. This shows the middle portion of a specimen with a height-diameter ratio of approximately two to one being confined by the excess material around it. Such material would have the effect of exerting a lateral confining pressure on the center section.

The strength of a confined specimen according to the Mohr theory is given by:

$$S_o = 2c\sqrt{K} + LK \qquad (8)$$

in which

$$K = \frac{(1 + \sin\phi)}{(1 - \sin\phi)}$$

ϕ = angle of internal friction
c = cohesion
L = confining pressure

Thus, strength is composed of elements involving the unconfined compressive strength ($2c\sqrt{K}$) plus a confining effect (LK) that depends upon the angle of internal friction of the material. Confining pressure "L" in the above equation must be considered to be an "effective" pressure rather than a uniformly applied pressure as employed in a rational triaxial test. McLeod (8) has asserted that the effective lateral support which becomes active in the Marshall test is not constant but depends upon:

1. Coefficient of friction between specimen and test head.
2. Maximum vertical load applied.
3. Angle of internal friction of the mix.
4. Shearing resistance of the material.

He has made use of these premises in a theory of pavement design (10) in which the importance of friction in the development of pavement stability is pointed out.

A review of the work by McLaughlin and Goetz reveals that the effective confining pressures as calculated on the basis of their Marshall Stability values are directly related to the applied vertical load in the test. Confinement behaves as if developed by the friction between the testing head and specimen. A reasonable approximation of this confinement can be obtained by taking 5.5 percent of the Marshall Stability/10. Thus, a stability of 1,000 lb tends to produce a confining pressure of 5.5 psi and 2,000 lb corresponds to 11 psi. While these figures are approximate, and frictional forces are probably not constant, this method provides a reasonable approach to the establishment of a relationship between Marshall Stability and unconfined compressive stress.

Substituting $L = 0.055\ \frac{(\text{Stability})}{10}$ in Eq. 8 and remembering that $S_o = \frac{\text{Stability}}{10}$, the equation becomes:

$$\frac{\text{Stability}}{10} = 2c\sqrt{K} + 0.055\ \frac{(\text{Stability})}{10}\ K \qquad (9)$$

$$\frac{\text{Stability}}{10} = \frac{2c\sqrt{K}}{1 - 0.055\ K}$$

By providing a reasonable measure of K which is a function of the angle of internal friction, it is possible to calculate the unconfined compressive stress from Marshall Stability results. The Purdue investigations (8) also showed that reasonably good correlation existed between the "flow" value in the Marshall test and actual measured values of the angle of internal friction. Although flow cannot be considered a direct measure of friction, the properties that affect friction appear to affect flow in a similar manner and thus the flow value offers a convenient, if inexact, means of estimating the friction angle. A rough estimate of internal friction can be obtained from:

$$\text{Angle of internal friction (degrees)} = 60 - \text{Flow} \qquad (10)$$

Evaluation of K on this basis permits the unconfined compressive stress to be estimated from Marshall results. A convenient expression for estimating K directly from the flow value is given by:

$$K = 3.5 + \left(\frac{30 - \text{Flow}}{10}\right)^2$$

Similarly, the quantity (1-0.055 K) in Eq. 9 can be estimated from:

$$(1 - 0.055\,K) = 0.1\left[8 - \tfrac{1}{2}\left(\frac{30 - \text{Flow}}{10}\right)^2\right]$$

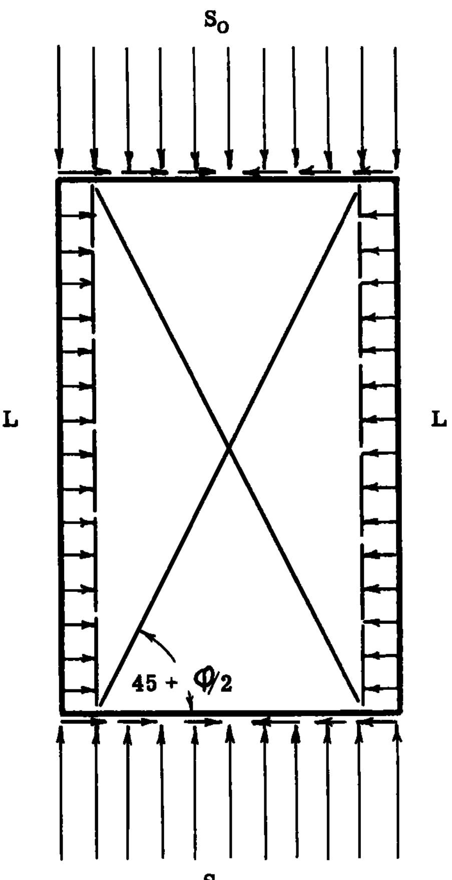

Figure 3. Confinement provided by specimen of low height-diameter ratio.

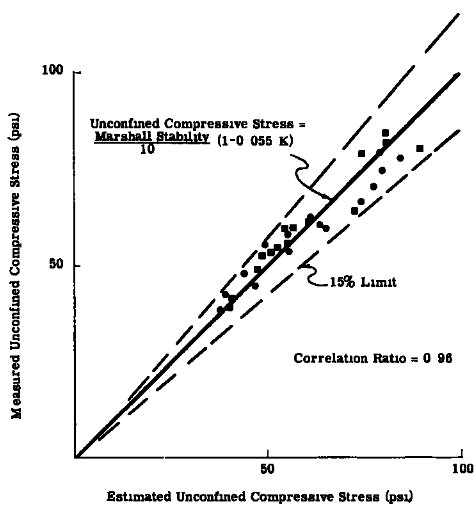

Figure 4. Correlation of measured unconfined compressive stress with unconfined compressive stress estimated from Marshall Stability test.

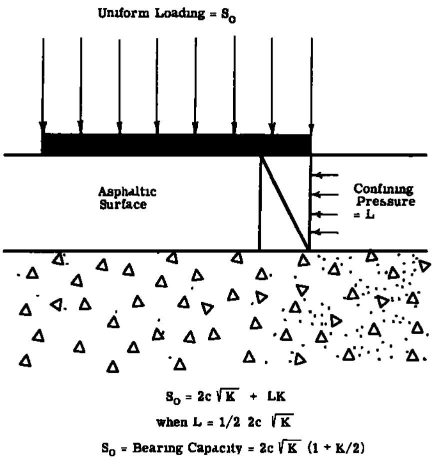

Figure 5. Bearing capacity of loaded pavement.

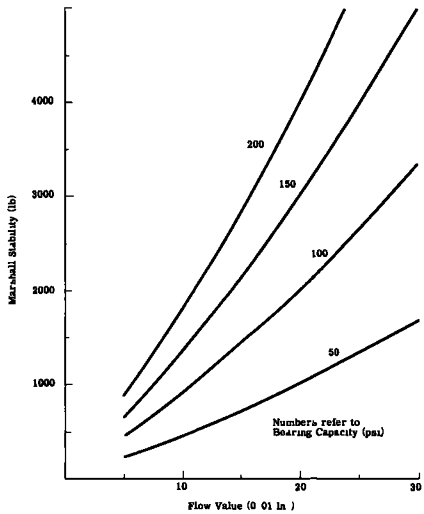

Figure 6. Bearing capacity curves based on Marshall Stability test.

Thus, the approximate unconfined compressive strength corresponding to a given Marshall Stability is:

$$2c\sqrt{K} = \frac{\text{Stability}}{100}\left[8 - \tfrac{1}{2}\,\frac{(30 - \text{Flow})^2}{(\ \ 10\ \ )}\right]$$

When estimated values of the unconfined compressive stress are compared with the values measured by McLaughlin and Goetz, the correlation shown in Figure 4 is produced. The correlation ratio of 0.96 between the two quantities indicates that the approximations made in this development are reasonable and that the Marshall Stability test can be described as a test involving differential confinement.

It is not intended to imply that the Marshall test is a form of triaxial test or should be substituted for triaxial testing. It does appear that, by proper interpretation, the Marshall results can be used to estimate useful information of a fundamental type.

APPLICATION OF MARSHALL STABILITY RESULTS TO PAVEMENT DESIGN

Eq. 8 indicates that the load-carrying ability of the critical element at the edge of a uniformly loaded area (Figure 5) in a pavement consists of the unconfined compression strength ($2c\sqrt{K}$) plus an allowance for the confinement provided by the surrounding material (LK). Analysis by McLeod (10, 11) has previously disclosed that frictional forces between load and pavement tend to increase the strength of the material at interior positions under the load.

In the previous section it was demonstrated that a reasonable estimate of unconfined compressive strength can be obtained from the Marshall Stability test. This strength, however, corresponds to a stress at which large deformations take place. Such great stresses are not generally acceptable for design purposes because they are accompanied by permanent deformations much larger than could be tolerated in any practical case. In order to limit plastic deformation it is necessary to select a portion of the unconfined strength that can be considered to be allowable for design purposes. Because surface deformation is the factor governing performance, allowable design stress should be based on the stress at equal deformations. Nijboer (12) has found that strains up to about one percent are essentially elastic and he has proposed this as a basis for calculation of allowable stress. One percent strain in the Marshall test occurs at a flow value of four and stresses calculated on this basis were accepted for design purposes.

Confinement provided by the material surrounding the loaded area must also be

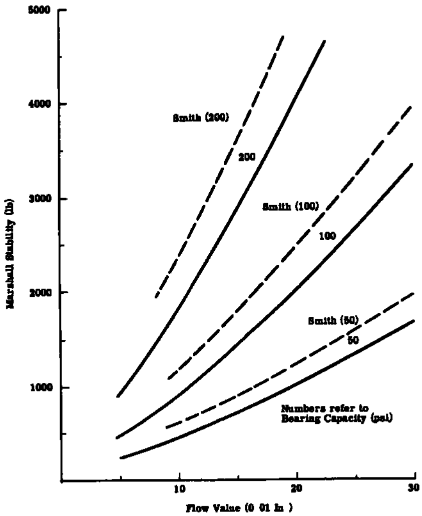

Figure 7. Comparison of bearing capacity curves with curves calculated from Smith Triaxial Design Method.

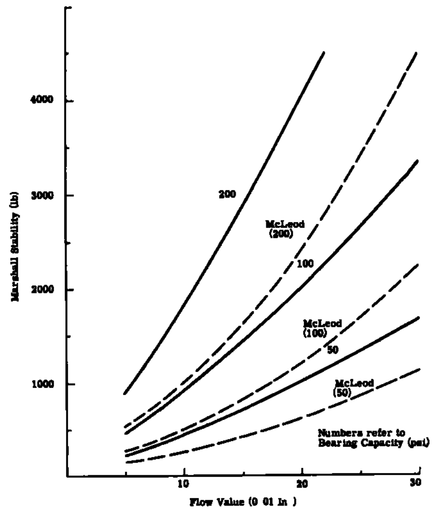

Figure 8. Comparison of bearing capacity curves with curves calculated from McLeod Method. (Confinement equals unconfined compressive strength).

estimated. McLeod (10) has suggested that the effective confining pressure can be taken equal to the unconfined compressive strength. Field experience has indicated, however, that this is too generous. Lateral pressures must be activated by lateral strain. For materials that do not change volume, lateral strain is equal to one-half the vertical strain and therefore it might be expected that 50 percent of the unconfined design stress represents the lateral confining pressure more reasonably. Such an allowance is similar to that made in the development of curves for preventing overstress at a point based on the theory of elasticity for Poisson's ratio = 0.5. These principles were employed by Smith (13) in the preparation of design curves for the closed-system triaxial test.

Combining the estimates of allowable design stress and lateral confinement it is possible to substitute in Eq. 8 to provide an expression for the bearing capacity of a mix in terms of Marshall Stability results.

$$S_o = 2c\sqrt{K} + LK \qquad (8)$$

Since unconfined compressive strength = 2c K and confining pressure = L = ½ (Unconfined compressive strength) then $S_o = 2c\sqrt{K} + K/2)$

allowable stress = S_o x 4/Flow = (4/Flow) $2c\sqrt{K}(1 + K/2)$ substituting the estimate of $2c\sqrt{K}$ from Eq. 9 $2c\sqrt{K} = \frac{\text{Stability}}{10}$ (1 - 0.055 K) this produces:

$$\text{Bearing capacity (psi)} = \tfrac{1}{5}\,(\text{Stability/Flow})\,(1-0.0055K)\,(K+2) \qquad (11)$$

Eq. 11 is the basis for the series of design curves in Figure 6, which show the Marshall Stability requirements corresponding to different intensities of uniform loading. Unit load figures on the curves are roughly equivalent to tire pressures of vehicles using the pavement. The 100 psi curve is considered to represent the maximum present intensity of highway loading.

Eq. 11 can be simplified to the form:

$$\text{Bearing capacity} = \frac{\text{Stability}}{\text{Flow}}\;\frac{(120 - \text{Flow})}{100} \qquad (12)$$

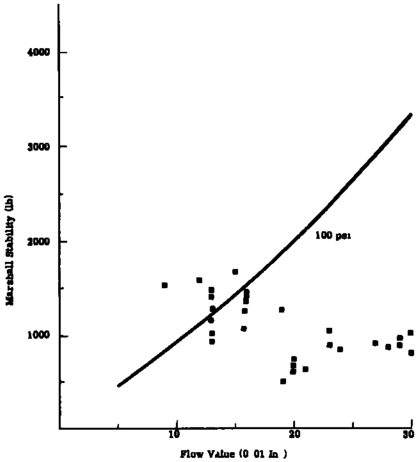

Figure 9. Stabilities of pavements with satisfactory resistance to plastic deformation.

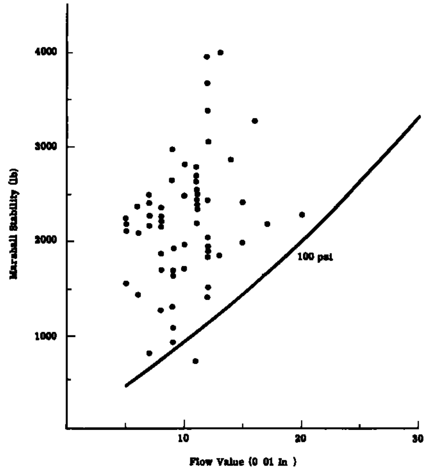

Figure 10. Stabilities of pavements showing excessive plastic deformation.

This is not an exact representation of Eq. 11 but it is sufficiently accurate for purposes of estimation.

Both equations emphasize that Marshall Stability alone is not an adequate measure of a pavement's ability to resist displacement. Stability and flow must be considered jointly.

Interesting comparisons of the above equation with the principles developed by Smith (13) and McLeod (10) are shown in Figures 7 and 8. These curves were calculated from the relationship between Marshall Stability and unconfined compressive strength. The Smith triaxial curves in Figure 7 are somewhat more conservative than those of Eq. 12, but both show similar trends. Differences between them, other than theoretical differences, might be caused by an imperfect relation between flow value and angle of internal friction. In the McLeod method, the allowance for confining pressures equal to unconfined compressive strength causes a substantial reduction in stability requirements. Stabilities calculated by each method illustrate these differences.

	Marshall Stability (lb) for 100 psi Bearing Capacity		
	Flow Value		
	10	15	20
McLeod Method	500	810	1195
Marshall Bearing Capacity	910	1430	2000
Smith Triaxial Method	1175	1785	2490

AGREEMENT OF THEORY WITH PERFORMANCE

A series of small-scale asphaltic concrete field test sections provided an excellent opportunity to investigate the validity of the bearing capacity equations developed above. These sections were constructed as part of a refinery entrance road at Wood River, Illinois, and were exposed to a large amount of truck traffic at temperatures that frequently reached 140 deg F in hot summer weather. During three and one-half years' service, performance of the sections was carefully observed for evidence of plastic displacement and core samples were taken periodically for measurements of the properties of the bituminous carpet.

Stabilities of pavements showing satisfactory performance during the test period are shown in Figure 9. These surfaces were judged to show no characteristics of plastic distress such as rutting, shoving, or flushing. Some were brittle or susceptible to raveling but had satisfactory resistance to plastic displacement at high temperatures

TABLE 1

PERFORMANCE AND CALCULATED BEARING CAPACITIES FOR WOOD RIVER ROAD TEST SECTIONS

No	Asphalt Pen Grade	Asphalt Content (% by weight)	Grading[1]	Marshall[2] Stab (lb)	Flow (0 01 in)	Calc[3] Bearing Capacity (psi)	Performance (Resistance to Plastic Displacement)
2A-16B	85/100	4	Dense	2370	6	450	Satisfactory
2A-19B	"	3 5	Open	2210	6	420	"
2A-18A	"	"	"	2500	7	404	"
2B-20A	"	"	"	3730	11	370	"
2A-10B	"	4	Dense	2120	6	403	"
2A-20A	"	3 5	Open	2105	6	400	"
2A-7B	"	4	Dense	2410	7	390	"
2B-18A	"	3 5	Open	4130	12	371	"
2B-10A	120/150	4	Dense	2970	9	366	"
2B-16A	85/100	3 5	Open	3975	12	357	"
2A-1A	40/50	4	Dense	2285	7	327	"
3A-3A	85/100	3 5	Open	3580	11	355	"
2A-19A	"	"	"	2190	7	354	"
3A-6B	"	"	"	3690	12	332	"
3A-4B	"	4	Dense	4005	13	329	"
3A-17A	"	3 5	Open	2385	8	334	"
2B-10B	"	4	Dense	2665	9	330	"
3A-1B	"	"	"	2260	8	317	"
3A-4A	"	"	"	2815	10	309	"
2B-4A	60/70	"	"	3380	12	304	"
2A-4B	85/100	"	"	2185	8	306	"
2A-16A	"	3 5	Open	2165	8	303	"
3A-5B	"	5	Dense	2810	11	279	"
2A-1B	"	4	"	1550	6	281	"
2B-13A	"	3 5	Open	2485	10	273	"
2B-7B	"	4	Dense	2700	11	268	"
3A-6A	"	3 5	Open	3055	12	275	"
2B-19A	"	3 5	"	2670	11	265	"
3A-7B	"	4	Dense	1460	6	277	"
2B-7A	"	4	"	2560	11	254	"
2A-10A	120/150	4	Dense	1870	8	262	"
2A-2A	40/50	5	"	2455	11	243	"
2A-4A	60/70	4	"	2440	11	242	"
2B-19B	85/100	3 5	Open	2380	11	236	"
3A-9B	"	"	"	1935	9	238	"
2A-14B	"	5	Dense	1705	8	238	"
3A-2B	"	5	"	2350	11	233	"
2B-1A	40/50	4	"	2895	14	219	"
3A-1A	85/100	4	"	2430	12	219	"
3A-3B	"	3 5	Open	2200	11	218	"
2A-7A	"	4	Dense	1980	10	218	"
2B-17A	"	3 5	Open	3175	16	206	"
2A-13A	"	"	"	1675	9	206	"
3A-8B	"	5	Dense	1665	9	205	"
2A-8A	"	"	"	1745	10	192	"
2B-12A	120/150	6	"	1555	9	192	Plastic
2B-14B	85/100	4	"	2040	12	183	Satisfactory
2B-8A	"	5	"	1895	12	171	"
2B-13B	"	4	"	1890	12	170	"
2A-5A	60/70	5	"	1880	12	169	"
2A-13B	85/100	4	"	1240	8	174	"
3A-5A	"	5	"	2410	15	169	"
2A-17B	"	"	"	2010	13	165	"
2A-14A	"	4 5	Open	1310	9	162	"
2B-4B	"	4	Dense	1865	13	153	"
3A-2A	"	5	"	1610	12	145	Plastic
2B-16B	"	4	"	1570	12	141	Satisfactory
2B-14A	"	4 5	Open	1995	15	140	"
2B-1B	"	4	Dense	1530	12	138	"
2B-5A	60/70	5	"	2190	17	133	"
3A-8A	85/100	5	"	1080	9	133	"
2B-11B	"	"	"	1425	12	128	"
2B-8B	"	"	"	1525	13	125	Plastic
2B-15B	"	6	"	1685	15	118	"
3A-7A	"	4	"	755	7	122	Satisfactory
2A-2B	"	5	"	1400	13	115	Plastic
2A-11B	"	"	"	940	9	116	Satisfactory
2B-2A	40/50	"	"	2290	20	114	"
2A-8B	85/100	"	"	1285	13	106	Plastic
2B-17B	"	"	"	1525	16	100	Satisfactory
2A-5B	"	"	"	1170	13	96	Plastic
2B-15A	"	5 5	Open	1465	16	95	"
2B-2B	"	5	Dense	1425	16	93	"
2A-11A	120/150	"	"	1025	13	84	"
2B-5B	85/100	"	"	1230	16	80	"
2A-9A	"	6	"	940	13	77	"
3A-9A	"	3 5	Open	725	11	72	Satisfactory
2A-15B	"	6	Dense	1060	16	69	Plastic
2A-15A	"	5 5	Open	1270	19	67	"
2B-6B	"	6	Dense	1045	23	44	"
2B-3B	"	"	"	905	23	38	"
2A-3B	"	"	"	730	20	36	"
2A-9B	"	"	"	685	20	34	"
2A-6B	"	"	"	855	24	34	"
2A-3A	40/50	"	"	920	27	32	"
2A-12A	120/150	"	"	645	21	30	"
2B-12B	85/100	"	"	605	20	30	"
2A-18B	"	"	"	975	29	30	"
2B-3A	40/50	"	"	1030	31	30	"
2A-12B	85/100	"	"	510	19	27	"
2B-6A	60/70	"	"	900	29	28	"
2B-18B	85/100	"	"	870	28	28	"
2A-6A	60/70	"	"	790	30	24	"

[1] Dense grading corresponds to Asphalt Institute Type IV Paving Mix Open grading is a Type II mix
[2] Average of four specimens
[3] Bearing capacity calculated from simplified equation. Stability/Flow $\frac{(120\text{-Flow})}{(\ 100\ )}$.

(140 deg F). The curve representing a uniform load of 100 psi is considered equal to the most severe loading imposed by truck tires. This seems a fair estimation of highway loading even though it has been shown (14, 15) that the rigidity of tire sidewalls causes non-uniform contact pressures.

Stabilities of all sections representing satisfactory performance except one are above the 100 psi curve indicating that theoretical bearing capacities as listed in Table 1 are greater than the loads imposed by traffic. A majority of the points representing sections with plastic distress in Figure 10 are in the area below the curve where bearing capacities are less than 100 psi. A few sections appear above the curve but the deviation is relatively small for most of them.

Bearing capacities calculated from the Marshall Stability test generally appear to be in good agreement with performance of the sections. The theory provides a reasonable method for predicting performance in the range of highway loading for pavements that are frequently exposed to temperatures near 140 deg F.

In addition to the small-scale test sections discussed above, cores have been taken from regular highway pavements which have been in service for several years. Performance of these pavements together with bearing capacities calculated from Marshall Stability tests are listed in Table 2. Although some variation exists in the type of construction and density of traffic, the agreement of theory and performance is reasonably good. All surfaces with bearing capacities above 100 psi are performing satisfactorily after ten years' service. Of the three surfaces with bearing capacities less than 100 psi, two show some evidence of plastic displacement. The behavior of these highways does not provide a rigorous test of the method for calculating bearing capacities but is in agreement with the predictions of the method.

Whether the curves can be successfully applied to the design of pavements that must support loads heavier than present highway loading has not been investigated directly. Equipment developing contact pressures of 200 psi, such as is produced by the wheels of military aircraft, has not been available. A limited examination of test results from the Corps of Engineers experiment station at Vicksburg shows a fair agreement between Marshall bearing capacities and performance under high pressure aircraft tires. Theoretical bearing capacity requirements are, however, more conservative than present engineer specifications for airfield pavements. The Corps of Engineers requires a minimum stability of 1,800 lb and maximum flow of 16 for pavements presumed to support contact pressures greater than 200 psi. Bearing capacity for this stability and flow is 117 psi. At the same flow value, a stability of 3,070 lb would be required for 200 psi and 3,850 lb for 250 psi loading. At a flow value of 10, however, the 1,800-lb stability corresponds to a 198 psi capacity and 2,270 lb is equal to 250 psi. Comparison of these figures demonstrates the importance of the flow value in bearing capac-

TABLE 2

PERFORMANCE AND CALCULATED BEARING CAPACITIES FOR HIGHWAY PAVEMENTS IN SERVICE

No.	Type of Construction	Traffic Density	Age (yr)	Marshall Stab (lb)	Flow (0.01 in.)	Calc Brg Capacity	Performance (Resistance to Plastic Displacement)
7	Resurfacing of PC concrete bridge deck	Very heavy	10	3020	13	257	Satisfactory
5	Resurfacing of PC concrete	Moderate	10	1820	12	168	"
3	Resurfacing of PC concrete	Light	10	1690	16	110	"
4	Resurfacing of flexible pavement	Light	10	1530	15	107	"
19	Resurfacing of PC concrete	Heavy	5	1165	14	88	Plastic
1	Resurfacing of PC concrete	Heavy	10	1700	20	85	Satisfactory
9	Resurfacing of	Heavy	10	1365	17	83	Plastic

ity calculations. It is hoped that the results of future tests will provide a basis for confirming the theoretical calculations in designs for high pressure tires.

It should be realized that bearing capacity curves for the Marshall Stability test are based on in-place properties of the material in the pavement. The ability of the Marshall test to make a satisfactory prediction of field performance will depend largely on whether or not specimens can be prepared in the laboratory that will reproduce the properties of material in the field. Thus, satisfactory design depends not only on the method of test but also on the preparation of material for testing.

CONCLUSION

It is believed that the method described for the derivation of bearing capacities from the results of the Marshall Stability test will lead to a better understanding of the test and to a more rational use of it in the design of highways and airfields. By providing a method for interpreting the empirical Marshall data in terms of fundamental properties, it is possible to design for different load conditions. The comparison of theory with field performance indicates that the necessary approximations in the theory are conservative and reasonable.

The Marshall test is not believed to be a rational test nor should it be used as a substitute for triaxial testing. Many situations occur, however, when it is necessary to design on the basis of the Marshall test alone. In these cases, reasonable estimates of fundamental properties which can be obtained from Marshall testing can aid in good design.

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