Evaluation of Marshall Stability and Flow Values of Asphaltic Paving Mixtures

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This study was conducted to investigate the effects of specimen thickness on both Marshall stability and Marshall flow. Correction factors were derived from regression analyses for both stability and flow, based on data from 18 mixes. Mixtures studied included both original plant mixes and remolded field cores. Thickness of specimens ranged from 0.5 to 3.2 in.

•ONE of the objectives of asphalt paving mixture design is to obtain a mixture with sufficient stability to satisfy, without detrimental distortion or displacement, the service requirements and demands of traffic. Stability of a compacted mixture may be defined as its resistance to such displacement or deformation. In the field, the term implies resistance to shoving and rutting by the action of traffic, and involves resistance to shearing stress. In mixture design, stability and many other mechanical properties have been determined experimentally in the laboratory (rather than calculated from theoretical stress-strain considerations) due to the heterogeneous and viscoelastic nature of the mixture and the complex stress conditions in a flexible pavement system. In the laboratory, stability is expressed in terms of stability tests on compacted mixtures by one or more of several available methods. Criteria have been developed for most of these methods by correlating the results of laboratory tests on compacted paving mixtures with the performance of the paving mixtures under service conditions.

In this approach, it is essential that laboratory methods of sample preparation and testing be able to reproduce, correlate, and predict conditions and behaviors of a mixture in the field during construction and while in service.

Many studies (1-5) have proposed establishing relationships between laboratory specimen compaction and field compaction, and between laboratory specimen density and field pavement density. However, no systematic study on the relationship between stability of laboratory-compacted specimens and stability of the mixture in pavement has been reported. It is often desirable or necessary to be able to evaluate the stability of an asphaltic mixture in a pavement in terms of laboratory design stability. Such an evaluation can provide an engineer the information to readjust laboratory design practice and criteria and field construction practice and control, and to study continuously the factors related to pavement behavior and the effects of time, density, and other environmental factors on stability of mixture in place or in an existing pavement. At present there is no reliable method or information to conduct such an evaluation.

For laboratory analyses there are two logical approaches:

1. Obtain slabs of pavement, remold them into design test specimens in the laboratory, and test for stability; and
2. Cut field cores the size of the design test specimen and test for stability.

Although testing cored samples has not been officially adopted by the ASTM as a standard method in evaluating paving mixtures in place, it is often done to get some information on the in-place mixture in question. This practice is also evidenced by the fact that the current Marshall method adopted by the ASTM actually suggests (6) that, for

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core specimens other than 2.5 in., the stability be corrected by multiplying the proper thickness correction factors as suggested by the Corps of Engineers.

In order to make evaluation or meaningful comparison, it is necessary, for either approach, to know the exact effects of specimen thickness on laboratory mixture stability because of the varied pavement thicknesses in place. This study was designed to investigate these effects in terms of the Marshall method.

MARSHALL FLOW VALUE

The Corps of Engineers (1) recognized that some device for measuring total strain of test specimens would be a valuable addition to the Marshall stability test. A flow meter, which measures the strain occurring in a test specimen between no load and maximum load in hundredths of an inch, was developed. The flow value is a measure of plasticity and flexibility of the compacted mixture and is considered an integrated part of the Marshall method in evaluating the quality of an asphaltic concrete mixture under traffic.

One of the primary factors affecting the flow value is the degree to which the aggregate voids are filled with asphalt. Therefore, for a particular aggregate gradation, the flow value is largely dependent on the asphalt content. A maximum flow value is usually established to prevent the use of excessive asphalt resulting in a plastic mix. A minimum flow value is recommended by the Asphalt Institute because mixes with abnormally low flow values tend to be brittle and less durable.

Goetz (7, 8) and Metcalf (9) have made important studies on the significance of flow value in a Marshall test. Goetz attempted to examine the results of Marshall testing in the light of more fundamental triaxial and unconfined compression tests. Two conclusions from this work are that the Marshall test is a type of confined test due to the curved shape of the testing heads, and that Marshall flow is a measure of internal friction of the compacted mixture. (An inverse linear relationship exists between the internal friction angle and Marshall flow.) By analyzing the stress conditions in a Marshall test and by applying a few assumptions, Metcalf was able to show that the bearing capacity of a paving mixture can be related to Marshall stability and flow by the following approximate form:

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

The approximate unconfined compressive strength corresponding to a given Marshall result is

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

More significantly, Metcalf showed that bearing capacities calculated from the Marshall test generally agreed with the performance of the test sections, thus demonstrating the importance of the flow value in the paving mixture design and especially in the evaluation of in-place properties of mixtures in pavement. It was again shown that the ability of the Marshall test (and the bearing capacity calculated from the Marshall test) to satisfactorily predict field performance depended largely on whether or not laboratory-prepared specimens could reproduce or be related to the properties of in-place material in the pavement.

The effect of sample thickness on flow value was studied within a limited range in the original studies of the Corps of Engineers. It was concluded that specimen thickness has little effect on flow, and thus no correction factors were considered necessary for flow value measured for specimens that were not of a standard 2.5-in. thickness. No published data of systematic study support or disprove this, although it was suspected by some that flow might be influenced by the thickness of the specimen. The Corps of Engineers conclusion was based on observations on specimens thicker than 1.5 in. Consequently, a study on specimen thickness effect on Marshall flow, especially for samples thinner than 1.5 in., is needed to properly evaluate Marshall test results on thinner specimens. This is especially desirable because thin hot-mix wearing surfacings are becoming more popular with highway engineers both in the United States and abroad.

MATERIALS AND METHODS

Materials used in this study were obtained in the field from three associated research projects conducted at the Bituminous Research Laboratory, Iowa State University, during the 1964, 1967, and 1968 construction seasons. Mixes were taken at the plants during the regular paving construction projects in Iowa. Four-in. cores were taken immediately after compaction for mixes No. 1 to 9. Cores were taken after 1 year of service from mixes No. 10 to 16. Core thicknesses varied from 0.6 in. to 2.5 in. Gradation and percent bitumen of these mixes are given in Table 1.

Plant mixes were heated in a laboratory oven to between 250 and 275 F and compacted to various thicknesses according to the standard Marshall method (50 blows on each side). Compacted specimens included duplicate samples of standard thickness (2.5 in.) and thicknesses equal to those of the pavement cores in which the mixes were placed.

Standard Marshall stability and flow at 140 F were determined for all samples after sample thickness was measured and bulk specific gravity was determined.

After testing, both laboratory-compacted specimens prepared from original plant mixes and field cores were remolded (by heating in the oven to 250 F) and compacted by the standard Marshall method. These were again tested for thickness, bulk specific gravity, Marshall stability, and flow.

RESULTS

Results of thickness effect study on mixes No. 1 to 9 are given in Table 2. Related information for mixes No. 10 to 16 is given in Table 3. Each set of data represents the average of at least two identical specimens.

Stability vs Specimen Thickness

The relationship between specimen thickness and stability at 140 F was studied by regression analysis for all mixes that were compacted by the standard Marshall method (50 blows per side) and that had more than three thicknesses. Correlation coefficients were also calculated for each mix. Linear equations of regression, sample size n, and correlation coefficient r are given in Table 4(a). For comparison, the equations of regression were also obtained by using the Corps of Engineers correction factors for standard stability of 500, 1000, and 2000 lb, designated in the table as CE 500, CE 1000,

TABLE 1

GRADATION AND BITUMEN CONTENT OF MIXES STUDIED

Property	Mix No.														
	10	11	12	13	14	15	16	1	2	3	4	6	7	8	9
Percent passing sieve															
1 in.	100	100	100	100	100	100	100								100
$^3/_4$ in.	100	100	100	100	100	99	100					100			
$^1/_2$ in.	97	91	95	93	96	91	92					94			78
$^3/_8$ in.	86	77	79	78	81	78	77	100	100	100	100	77	100	100	62
No. 4	65	56	59	57	63	60	59	81	89	92	78	60	85	85	49
No. 8	51	44	46	45	52	48	47	62	67	58	59	43	67	63	
No. 16	36	37	33	34	41	34		44							
No. 30	28	32	25	27	31	27	28	30	34	34	31	25	35	35	23
No. 50	16	21	17	19	18	17	19	16	21	23	18	19	25	25	
No. 100	8	10	12	12	12	9	12	12	13	13	13	9		13	
No. 200	5.7	7.7	7.8	8.0	8.5	7.2	7.0	9.3	9.9	9.4	9.4	7.1	8.4	8.9	6.7
Percent bitumen	5.3	5.7	5.5	5.3	4.8	4.3	4.8	7.5	6.3	6.3	7.5	5.0	7.0	5.3	5.5
Year	1964	1964	1964	1964	1964	1964	1964	1967	1967	1967	1967	1968	1968	1968	1968

TABLE 2

EFFECT OF THICKNESS ON STABILITY, FLOW, AND BEARING CAPACITY OF MIXES NO. 1 TO 9

Mix No.	Type of Mix	Percent Bitumen	Thickness (in.)	Specific Gravity	Stability (lb)	Flow (0.01 in.)	Bearing Capacity (psi)	Corrected Bearing Capacity (psi)
1	P	7.5	0.79	2.35	400	5	92.0	291.1
			0.91	2.34	490	4	142.1	390.4
			1.11	2.33	690	4	200.1	450.7
			1.27	2.28	520	5	119.0	235.4
			1.35	2.32	840	4	243.6	447.8
			1.52	2.24	750	7	121.1	199.1
			1.61	2.35	1250	5	287.5	446.4
			2.12	2.34	1800	7	296.6	342.7
			2.54	2.31	2060	7	332.5	327.3
2	P	6.3	0.93	2.25	600	5	138.0	370.9
			1.09	2.20	570	6	108.3	248.4
			2.45	2.19	1920	16	124.8	126.8
			2.60	2.18	2000	15	140.0	134.6
			2.93	2.07	2350	11	232.9	198.7
	CR-O	6.3	0.94	2.25	460	6	87.4	232.5
			1.04	2.28	660	5	151.8	364.9
			2.41	2.21	1650	10	181.5	188.3
			2.50	2.24	2200	8	308.0	308.0
			2.65	2.22	2100	10	231.0	217.9
3	P	6.3	0.95	2.280	400	5	92.0	239.6
			1.03	2.292	500	5	115.0	279.1
			1.22	2.260	520	5	119.6	245.1
			1.31	2.271	650	5	149.5	285.3
			1.45	2.282	850	5	195.5	343.8
			1.54	2.302	1080	5	248.4	403.3
			2.51	2.288	2020	9	249.1	248.1
	CR-O	6.3	0.89	2.324	490	5	112.7	316.6
			1.03	2.298	520	5	119.6	290.3
			1.13	2.342	760	6	144.4	319.5
			1.28	2.332	880	7	142.0	277.5
			2.57	2.322	2390	9	294.8	286.7
4	P	7.5	0.99	2.239	580	6	109.2	278.3
			1.14	2.278	1380	6	262.2	574.9
			2.45	2.223	2710	10	298.1	302.9
			2.74	2.206	2830	14	214.3	195.5
	P + 1	7.5	0.81	2.302	650	6	122.6	381.2
			1.13	2.258	850	6	161.5	357.3
			2.53	2.230	2550	12	229.5	226.8
	CR-O	7.5	0.89	2.345	980	6	185.3	523.0
			1.12	2.296	1150	6	218.5	487.7
			1.25	2.282	980	6	186.2	372.8
			1.40	2.268	1090	6	206.2	369.8
4	CR-O	7.5	1.55	2.258	1180	7	199.7	307.2
			1.70	2.247	1200	7	228.0	284.9
			2.65	2.242	2720	10	298.7	282.3
6	P	5.0	1.44	2.40	1035	6	196.6	341.4
			1.58	2.39	960	6	182.4	288.6
			1.70	2.41	1285	6	244.1	359.0
			1.72	2.40	1270	6	241.3	350.7
			1.73	2.37	1160	6	220.4	318.5
			1.83	2.40	1590	6	302.1	412.7
			1.98	2.39	1500	6	285.0	359.9
			2.13	2.38	1440	7	232.4	272.8
			2.39	2.39	1990	9	245.4	256.7
7	P	7.0	0.59	2.32	240	4	69.6	294.9
			0.71	2.31	260	4	75.4	265.5
			0.72	2.31	270	4	78.3	271.9
			0.86	2.29	215	4	62.4	181.3
			0.98	2.29	335	4	97.2	247.8
			1.11	2.28	365	4	105.8	238.4
			1.25	2.27	370	5	85.1	170.2
			1.38	2.28	495	4	143.6	260.1
			1.52	2.28	540	4	156.6	257.6
			1.64	2.28	570	5	131.1	199.9
			2.14	2.31	1275	6	242.2	283.0
8	P	5.3	0.54	2.33	270	6	51.3	237.5
			0.69	2.29	260	6	49.4	178.9
			0.81	2.31	345	5	79.4	244.9
			0.93	2.32	440	6	83.6	224.7
			1.05	2.33	590	6	112.1	266.9
			1.18	2.34	610	6	115.9	245.6
			1.30	2.33	735	7	117.0	225.1
			1.43	2.34	935	7	150.9	263.9
			1.56	2.34	1065	6	202.4	324.3
			2.22	2.33	1710	7	276.0	310.9
	CR-O	5.3	0.54	2.33	235	6	44.6	206.7
			0.69	2.32	290	6	55.1	199.6
			0.80	2.33	345	7	55.7	174.0
			0.92	2.33	415	6	78.8	214.3
			2.43	2.33	1805	8	252.7	259.9
9	P	5.5	1.12	2.37	570	6	108.3	241.7
			1.28	2.39	760	6	144.4	282.0
			1.78	2.37	1120	6	212.8	298.9
			1.87	2.39	1375	6	261.2	349.3
			2.16	2.36	1240	7	200.2	231.7
			2.43	2.37	1860	7	300.3	308.1

CR-O Remolded O-month core

P Original plant mix

P + 1 One hour after leaving plant

TABLE 3

PROPERTIES OF MIXES NO. 10 TO NO. 16

Mix No.	Type of Mix	Thickness (in.)	Specific Gravity	Stability (lb)	Flow (0.01 in.)	Bearing Capacity (psi)	Corrected Bearing Capacity (psi)
10	P	2.50	2.36	1510	12	135.9	135.9
		2.94	2.36	1700	14	128.9	109.5
		3.19	2.38	1950	16	126.8	99.3
11	P	2.56	2.32	2490	9	307.1	299.9
		2.63	2.33	2650	11	262.6	249.6
		2.81	2.31	3020	19	160.5	142.8
		3.13	2.32	3240	22	144.3	115.3
12	P	1.31	2.35	980	8	137.2	261.8
		1.50	2.34	1200	9	148.0	246.7
		1.81	2.30	1280	12	115.2	159.1
		1.94	2.30	1500	11	148.6	191.5
		2.13	2.31	1860	10	204.6	240.1
		2.56	2.33	2540	13	209.1	204.2
13	P	2.50	2.40	1570	8	219.8	219.8
	CR-12	2.13	2.36	1650	10	181.5	213.0
		2.25	2.37	1770	10	194.7	216.3
		2.50	2.35	1950	11	193.2	193.2
		2.56	2.36	2050	12	184.5	180.2
14	P	2.50	2.26	1330	8	172.2	172.2
	CR-12	1.44	2.28	300	7	48.4	84.1
		1.50	2.30	340	12	30.6	51.0
		1.56	2.29	380	13	31.3	50.1
15	P	2.50	2.40	1400	10	154.0	154.0
	CR-12	2.00	2.45	680	15	47.6	59.5
		2.06	2.45	770	17	46.6	56.6
		2.13	2.45	930	18	52.7	61.9
		2.50	—	1230*	18	69.7	69.7
16	P	2.50	2.32	1440	9	177.6	177.6
	CR-12	2.50	2.36	1240	20	62.0	62.0
		2.56	2.36	1480	21	69.8	68.4
		2.63	2.36	1510	20	75.5	71.8
		2.69	2.35	1680	24	67.2	62.5

P Original plant mix
CR-12 Remolded 12-month core

*Corrected stability

TABLE 4

EFFECT OF THICKNESS

(a) Thickness t vs Stability S

Mix No. and Type	Equation	Sample Size n	Correlation Coefficient r	Standard-Size Specimen Stability So
1 P	$S = 1019\ t - 520$ $= 0.495\ S_ot - 0.253\ S_o$	9	0.9622*	2060
2 P	$S = 907\ t - 328$ $= 0.463\ S_ot - 0.167\ S_o$	5	0.9969*	1960
2 CR-O	$S = 939\ t - 378$ $= 0.427\ S_ot - 0.172\ S_o$	5	0.9779*	2200
3 P	$S = 1071 - 674$ $= 0.530\ S_ot - 0.307\ S_o$	7	0.9897*	2020
3 CR-O	$S = 1158\ t - 590$ $= 0.503\ S_ot - 0.257\ S_o$	5	0.9977*	2300
4 P	$S = 1174 - 276$ $= 0.433\ S_ot - 0.102\ S_o$	4	0.9688*	2710
4 P + 1	$S = 1138\ t - 345$ $= 0.446\ S_ot - 0.135\ S_o$	3	0.9968*	2550
4 CR-O	$S = 1003\ t - 184$ $= 0.371\ S_ot - 0.068\ S_o$	7	0.9226*	2700
6 P	$S = 977\ t - 433$ $= 0.489\ S_ot - 0.217\ S_o$	9	0.9035*	2000
7 P	$S = 577\ t - 228$ $= 0.444\ S_ot - 0.175\ S_o$	11	0.9063*	1300**
8 P	$S = 901\ t - 358$ $= 0.475\ S_ot - 0.191\ S_o$	10	0.9879*	1900**
8 CR-O	$S = 863\ t - 311$ $= 0.469\ S_ot - 0.169\ S_o$	5	0.9964*	1840
9 P	$S = 868\ t - 385$ $= 0.482\ S_ot - 0.214\ S_o$	6	0.9499*	1800
10 P	$S = 614\ t - 47$ $= 0.407\ S_ot - 0.031\ S_o$	3	0.9722	1510
11 P	$S = 1291\ t - 742$ $= 0.518\ S_ot - 0.298\ S_o$	4	0.9609*	2490
12 P	$S = 1222\ t - 731$ $= 0.481\ S_ot - 0.288\ S_o$	6	0.9675*	2540
13 CR-12	$S = 873\ t - 206$ $= 0.448\ S_ot - 0.106\ S_o$	4	0.9932*	1950
14 C-12	$S = 544\ t - 476$ $= 0.641\ S_ot - 0.560\ S_o$	3	0.9997*	850
15 CR-12	$S = 1933\ t - 395$ $= 1.172\ S_ot - 1.936\ S_o$	4	0.9935	1650**
16 CR-12	$S = 2090\ t - 3947$ $= 1.713\ S_ot - 3.234\ S_o$	4	0.9537*	1240
CE 500	$S = 296\ t - 242$ $= 0.592\ S_ot - 0.484\ S_o$	15	0.9966*	500
CE 1000	$S = 592\ t - 484$ $= 0.592\ S_ot - 0.484\ S_o$	15	0.9966*	1000
CE 2000	$S = 1185\ t - 968$ $= 0.592\ S_ot - 0.484\ S_o$	15	0.9966*	2000

(b) Thickness t vs Flow F

Mix No. and Type	Equation	Sample Size n	Correlation Coefficient r	Standard-Size Specimen Flow Fo
1 P	$F = 1.79\ t + 2.7$ $= 0.256\ F_ot + 0.386\ F_o$	9	0.7652*	7
2 P	$F = 4.60\ t + 1.4$	5	0.8438	—
2 CR-O	$F = 2.47\ t + 3.1$ $= 0.309\ F_ot + 0.388\ F_o$	5	0.9138*	8
3 P	$F = 2.66\ t - 1.7$ $= 0.296\ F_ot - 0.196\ F_o$	7	0.9144*	9
3 CR-O	$F = 2.33\ t + 3.2$ $= 0.259\ F_ot + 0.356\ F_o$	5	0.9465*	9
4 P	$F = 4.06\ t + 1.6$ $= 0.406\ F_ot + 0.160\ F_o$	4	0.9494*	10
4 P + 1	$F = 3.73\ t + 2.4$	3	0.9846	
4 CR-O	$F = 2.46\ t + 3.2$ $= 0.246\ F_o + 0.320\ F_o$	7	0.9574*	10
6 P	$F = 2.89\ t + 1.1$ $= 0.361\ F_ot + 0.137\ F_o$	9	0.8319*	8
7 P	$F = 1.12\ t + 3.1$ $= 0.187\ F_ot + 0.500\ F_o$	11	0.7802*	6
8 P	$F = 0.83\ t + 5.2$ $= 0.119\ F_ot + 0.743\ F_o$	10	0.6435*	7
8 CR-O	$F = 1.03\ t + 5.5$ $= 0.129\ F_ot + 0.688\ F_o$	5	0.8830*	8
9 P	$F = 0.83\ t + 4.9$	6	0.8048	—
10 P	$F = 5.65\ t - 2.3$	3	0.9876	—
11 P	$F = 23.10\ t - 49.0$	4	0.9422	—
12 P	$F = 3.49\ t + 3.9$ $= 0.268\ F_ot + 0.300\ F_o$	6	0.8344*	13
13 CR-12	$F = 4.33\ t + 0.5$	4	0.9225	—
14 CR-12	$F = 5.09\ t - 2.9$	4	0.7077	—
15 CR-12	$F = 22.83\ t - 30.4$	3	0.9726	—
16 CR-12	$F = 16.83\ t - 22.4$	4	0.7349	—

TABLE 4 (Continued)

(c) Thickness t vs Bearing Capacity B

Mix No. and Type	Equation	Sample Size n	Correlation Coefficient r
1 P	B = 129.59 t + 13.3	9	0.8168*
2 P	B = 32.35 t + 84.0	5	0.6134
2 CR-O	B = 80.35 t + 38.6	5	0.8149
3 P	B = 102.9 t + 19.6	7	0.8270*
3 CR-O	B = 109.89 t + 11.1	5	0.9951*
4 P	B = 44.86 t + 138.7	4	0.4898
4 P + 1	B = 58.06 t + 84.7	3	0.9816
4 CR-O	B = 62.65 t + 121.6	7	0.8933*
6 P	B = 59.06 t + 130.6	9	0.4528
7 P	B = 103.77 t - 8.3	11	0.9242*
8 P	B = 140.66 t - 40.9	10	0.9796*
8 CR-O	B = 113.63 t - 24.9	5	0.9971*
9 P	B = 126.38 t - 19.6	6	0.8911*
10 P	B = -13.55 t + 169.4	3	-0.9861
11 P	B = -277.02 t + 989.4	4	-0.8937
12 P	B = 64.40 t + 39.7	6	0.7598
13 CR-12	B = 6.31 t + 173.6	4	0.1987
14 CR-12	B = 22.39 t + 3.6	4	0.7540
15 CR-12	B = 40.55 t - 34.7	3	0.8065
16 CR-12	B = 33.83 t - 19.2	4	0.4980

(d) Thickness t vs Corrected Bearing Capacity B

Mix No. and Type	Equation	Sample Size n	Correlation Coefficient r
1 P	B = -11.68 t + 365.0	9	-0.7010*
2 P	B = -88.35 t + 392.8	5	-0.8163
2 CR-O	B = -36.29 t + 331.6	5	-0.4227
3 P	B = 4.09 t + 284.9	7	0.0356
3 CR-O	B = -12.49 t + 315.3	5	-0.4517
4 P	B = -110.16 t + 539.8	4	-0.5994
4 P + 1	B = -90.81 t + 457.1	3	-0.9994*
4 CR-O	B = -133.12 t + 576.2	7	-0.7864*
6 P	B = -77.51 t + 471.0	9	-0.4563
7 P	B = -6.11 t + 249.9	11	-0.0694
8 P	B = 65.03 t + 176.1	10	0.7534*
8 CR-O	B = 34.89 t + 173.4	5	0.8575
9 P	B = 24.25 t + 242.3	6	0.2781
10 P	B = -53.81 t + 269.7	3	-0.9955*
11 P	B = -312.95 t + 1072.7	4	-0.9120
12 P	B = -37.14 t + 286.9	6	-0.4269
13 CR-12	B = -77.94 t + 384.6	4	-0.9305
14 CR-12	B = -3.86 t + 68.2	4	-0.1152
15 CR-12	B = 23.53 t + 10.8	4	0.3422
16 CR-12	B = 8.28 t + 44.6	4	0.1454

*Significant at 5 percent level

**Estimated stability

So = Stability for standard size 2.5-in. specimen

Fo = Flow value for standard size 2.5-in. specimen

and CE 2000. Since the equations are functions of standard stability (stability of standard 2.5-in. specimen), they were also expressed in terms of standard stability So in the following form:

$$S = a\,So\,t + b\,So$$

where

S = stability of specimen with thickness t, lb;
So = stability of 2.5-in. specimen, lb;
t = thickness of specimen, in.; and
a, b = constants (a being the slope, b the y intercept).

The following can be noted:

1. Stability is significantly correlated with thickness of specimen for all mixes over the thickness range studied (i. e., from 0.5 in. to 3.2 in.) regardless of the type of mix, asphalt content, aggregate gradation, cores or remolded cores, as long as the compactive efforts are the same.

2. The relation between stability and thickness is linear. When expressed in terms of standard stability So, the relation can be stated as

$$S = a\,Sot - b\,So$$

Constant a varied from 0.37 to 1.71 and constant b varied from 0.03 to 3.23. If core samples are disregarded due to small sample size and possible variation due to coring, the ranges of a and b are narrowed to between 0.37 and 0.53 for a and between 0.07 and 0.31 for b for those mixes whose correlation coefficients are significant at the 5 percent level. The averages of all these mixes are 0.47 for a and 0.20 for b, compared with the constants derived from the Corps of Engineers data of 0.59 and 0.48 respectively. Assuming that the relationship is linear over the range of thickness of 0.5 in. to 3.5 in., the comparsion in Table 5 can be made between this study and the Corps of Engineers data for a mixture with a standard stability of 1000 lb.

From Table 5 it is obvious that the Corps of Engineers correction factors cannot be used for specimens or cores less than 1 in. thick, which are often used for thin hot-mix wearing courses.

Flow vs Specimen Thickness

The relationship between Marshall flow and specimen thickness in terms of equations of regression and correlation coefficients is given in Table 4(b). Except for core samples, coefficients were positive and significant for essentially all mixes regardless of type of mix and asphalt content. The relation was linear—an increase in thickness resulted in higher flow value for the same mix and compactive effort. The table also shows the flow value F at thickness t as a function of standard-size specimen flow Fo for all the mixes that showed significant correlation at the 5 percent level. The average equation relating F, Fo, and t for all mixes is

$$F = 0.26\,Fot + 0.35\,Fo$$

For a mix with a flow of 10 at 2.5 in., a difference of 0.5 in. in specimen thickness will mean a difference of one unit in flow. As an approximation the correction factors for flow for specimens other than 2.5 in. thick should be

Thickness (t)	Correction Factor	Thickness (t)	Correction Factor
0.5	2.08	2.5	1.00
1.0	1.64	3.0	0.88
1.5	1.35	3.5	0.79
2.0	1.15		

The Corps of Engineers recommendation that flow correction is not necessary is essentially correct within a narrow range of thickness variation, since the flow change is not sensitive to small thickness change.

Bearing Capacity vs Specimen Thickness

It has been repeatedly pointed out by many that the Marshall stability alone cannot adequately measure the ability of a paving mixture to resist displacement under load. Bearing capacities, as suggested by Metcalf (9), were calculated for all specimens and mixes because they offer means of evaluating Marshall stability and flow jointly. The relationship between specimen thickness and bearing capacity, as calculated directly from stability S and flow F of specimens of varied thickness $[B = S/F \times (120 - F)/100]$, is given in Table 4(c). The relationship between thickness and bearing capacity when thickness is taken into consideration $[B = S/tF \times (120 - F)/140]$ (termed as corrected bearing capacity) is given in Table 4(d).

TABLE 5

COMPARISON OF DATA

Thickness t (in.)	Iowa State University $S = So(0.47t - 0.20)$ $= 470t - 200$		Corps of Engineers $S = So(0.59t - 0.48)$ $= 590t - 480$	
	Stability S (lb)	Correction Factor	Stability S (lb)*	Correction Factor*
0.5	35	28.60	-165 (—)	— (—)
1.0	270	3.70	110 (180)	9.10 (5.56)
1.5	505	1.98	405 (450)	2.47 (2.78)
2.0	740	1.35	700 (680)	1.43 (1.47)
2.5	980	1.02	1000 (1000)	1.00 (1.00)
3.0	1210	0.83	1290 (1320)	0.78 (0.76)
3.5	1450	0.69	1590 (—)	0.63 (—)

*Figures in parentheses were obtained by using the recommended correction factors rather than from the regression equation

Eight of the 20 mixes indicated significant correlation between thickness and uncorrected bearing capacity, all positive. This is to be expected since the stability increases with increasing sample thickness. However, no general equation can be established either as a function of thickness t or in terms of thickness t and standard bearing capacity Bo.

Theoretically the corrected bearing capacity of a mixture should be independent of specimen thickness. Data in Table 2 and the correlation coefficients in Table 4(d) generally support this. The fact that 5 of the 20 mixes showed significant correlation could be attributed to: (a) the assumption that the stability is directly proportional to specimen thickness in corrected bearing capacity calculation, and (b) measurement error or repeatability of the stability test.

CONCLUSIONS

Within the limits of this study, the following conclusions can be drawn:

1. Both Marshall stability and flow should be corrected to properly evaluate and compare specimens of nonuniform and nonstandard thicknesses. The Corps of Engineers correction factors are not adequate for thin specimens.
2. Further research is needed to establish criteria for evaluating results of stability tests on core specimens and evaluating flow values of specimens other than standard size.

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