APPRAISAL OF SEVERAL METHODS OF TESTING ASPHALTIC CONCRETE

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FOREWORD

During the past twenty years a number of laboratory methods have been developed for compacting asphaltic concrete mixtures and testing them for stability or resistance to displacement under load. Their use has brought speculation by engineers as to correlation between methods.

In research to determine correlation the Texas Engineering Experiment Station tested about 1600 specimens of asphaltic concrete. The work involved study of six laboratory methods of test for stability and of three compaction procedures.

Correlation between results of the six stability test procedures ranged from none to rather good. Different stability test procedures were found to measure the fundamental factors of internal friction and cohesion in quite different ways. Data were also obtained on the manner of variation of the stability values with change in type of aggregate, change in asphalt content, change in hardness of asphalt, and change in compaction procedure.

The research brought out also that one of the greatest needs in the field of testing of asphaltic concrete is agreement on a standard procedure for laboratory compaction of the specimens for testing.

Details of the experimentation are presented in this bulletin for the information of the working group in highway technology.

ACKNOWLEDGMENT

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SUMMARY

This bulletin presents the results of a rather extensive study of asphaltic concrete test procedures. Three methods of compaction—the Marshall method, the Texas Highway Department method, and the Asphalt Institute method—were used. Six stability test procedures—the Hveem stability test, the Marshall stability test, the direct compression test, the Asphalt Institute stability test, the cohesiometer test, and a modification of the Texas Highway Department punching shear test—were studied. The primary objectives of the studies were: (1) to determine whether or not correlation existed between the various test procedures, (2) to study the effect of variations in type of aggregate, quantity of asphalt, and grade of asphalt on the various stability values, and (3) to study the effect of compaction procedure on the density of the mixtures and on the results of the stability tests.

The three compaction procedures were found to produce significant differences in density. The Marshall and Texas Highway Department procedures were studied for all of the stability procedures except the Asphalt Institute and were found to produce specimens showing considerable difference in stability values for all test procedures except the Hveem. These differences indicate a definite need for agreement on a laboratory compaction procedure for asphaltic concrete mixtures.

No correlation was found between the results of the Hveem stability test and the results of the other stability test procedures. Some correlation was found between the other stability test procedures. The correlation ranged in degree from good to very poor.

All of the stability test results except those from the Hveem stability test were materially influenced by the grade of asphalt cement used in the mixture.

The Marshall stability, Texas Highway Department punching shear, the ultimate strength in direct compression, and the Asphalt Institute stability test results all show the same type of variation in stability with variation in asphalt content.

For the Marshall compaction procedure and a given grade of asphalt the maximum stability values for the Marshall stability, the ultimate strength in direct compression, the Asphalt Institute stability and the Hveem stability all indicate approximately the same difference in aggregate characteristics for the four aggregate combinations studied. The Hveem stability test is considered to be the best for studying the characteristics of the mixture which are dependent on the type of aggregate.

INTRODUCTION

Asphaltic concrete pavements are plant mixtures of aggregates and asphaltic materials usually laid and compacted by machine. The requirements normally placed on the compacted mixture are those for stability (ability to resist the traffic load) and those for density. It is generally considered that the stability of asphaltic concrete mixtures is dependent upon the shear strength of the compacted mixture. The shear strength of granular materials is a function of the intergranular resistance to sliding or internal friction and the intergranular resistance to being pulled apart (cohesion).

A number of methods for determining the stability of asphaltic concrete mixtures are in present day use. These test methods measure the stability of the mixture in a more or less arbitrary manner, and their value lies in the extent to which the stability value obtained from the test has been correlated with the performance of the material in the pavement. Little work has been done with the idea of establishing the relationship between these variable test procedures and this research was instituted with the major objective of studying the relation between a number of the commonly used test procedures.

The specific objectives of this research project were as follows:

1. A study of six methods for determining the stability of asphaltic concrete to determine whether or not correlation exists between the methods. The stability methods studied were: Hveem stabilometer,[4,5,6,10] Marshall stability,[3,7] Texas Highway Department punching shear,[8] direct compression,[11,12] cohesiometer,[5] and Asphalt Institute stability test.[2]

2. A study of the effect of variations in type of aggregate, percentage of asphalt in the mixture, and hardness of asphalt upon the stability values found by the six procedures.

3. A study of the effect of three methods of preparing laboratory specimens—(1) the Marshall compaction method, (2) the gyratory compaction method used by the Texas Highway Department, and (3) the Asphalt Institute compaction method—upon the density of various asphaltic concrete mixtures.

4. A study of the effect of two methods of preparing laboratory specimens—the Marshall compaction method and the gyratory compaction method used by the Texas Highway Department—upon the stability values found by the following methods: Hveem stabilometer, Marshall stability, Texas Highway Department punching shear, direct compression, and cohesiometer.

The six stability test procedures selected for study cover those most widely used for the testing of asphaltic concrete in the United States and cover a wide range of type of test.

MATERIALS AND MIXTURES

The major portion of about 1600 specimens tested were prepared using standard aggregates and aggregate combinations. The aggregates used in the project were as follows:

1. Crushed limestone in various sizes.

2. Limestone dust obtained from the crushed limestone by grinding it in a ball mill and screening through a No. 200 sieve.

3. Washed gravel.

4. Washed sand originally intended for use in portland cement concrete from which the fraction larger than the No. 10 sieve was discarded for this project. This sand is hereafter referred to as sand A.

5. A field sand or blow sand which was prepared for use by washing it over a No. 200 sieve in order to remove the major portion of the silt and clay and by screening it over a No. 10 sieve. This sand is hereafter referred to as sand B.

Five sieve analyses were run on each of the aggregates except the limestone dust. The average values obtained from these sieve analyses are shown in Table 1.

The bulk specific gravity of the aggregates was obtained by the "Standard Method of Test for Specific Gravity and

Absorption of Fine Aggregate" (AASHO T 84-45 and ASTM C 128-42) except that a vacuum was used to remove the air from the water. Three bulk specific gravity determinations were made for each material. The bulk specific gravity was checked by using the pycnometer method employed by the Texas Highway Department. The average specific gravities of the materials are shown in Table 1.

TABLE 1

SIEVE ANALYSIS AND SPECIFIC GRAVITY OF AGGREGATES USED IN ASPHALTIC CONCRETE MIXTURES

Fine Aggregates (Predominately Finer than No. 10 Sieve)

	Sand A	Sand B	Limestone Screenings	Fraction of Limestone Screenings Passing No. 10 Sieve
Pass ¼" screen, ret'd. no. 10 sieve, per cent			12.2	
Pass no. 10 sieve ret'd. no. 40 sieve, per cent	51.2	2.5	47.6	54.2
Pass no. 40 sieve ret'd. no. 10 sieve, per cent	42.6	37.7	13.4	15.3
Pass no. 80 sieve ret'd. no. 200 sieve, per cent	5.8	56.9	9.5	10.8
Pass no. 200 sieve	0.4	2.9	17.3	19.7
Specific gravity	2.624	2.622	2.573	2.573

Coarse Aggregates (Predominately Coarser than No. 10 Sieve)

	Crushed Limestone ⅜"-¼"	Crushed Limestone ¼"-No. 10	Washed River Gravel ⅜"-No. 10
Pass ⅝" screen, ret'd. ½" screen, per cent	3.8	0.0	0.0
Pass ½" screen, ret'd. ¼" screen, per cent	94.9	10.4	46.1
Pass ¼" screen, ret'd. no. 10 sieve, per cent	1.3	77.9	44.3
Pass no. 10 sieve, ret'd. no. 40 sieve, per cent	0.0	11.3	8.6
Pass no. 40 sieve, per cent	0.0	0.3	1.0
Specific gravity	2.525	2.516	2.624

Mineral Fillers

	Portland Cement	Limestone Dust
Pass no. 80 sieve, ret'd. no. 200 sieve, per cent	3.0	0.0
Pass no. 200 sieve, per cent	97.0	100.0
Specific gravity	3.100	2.725

The asphalt cements used in preparing the asphaltic concrete mixtures were obtained from the Texas Company. The

four grades of asphalt cements used conformed to the Texas Highway Department specifications.

The specific gravities of the asphalt cements were obtained in accordance with the "Standard Method of Test for Specific Gravity of Bituminous Materials" (AASHO T 43-35) using the pycnometer method. The grades of asphalt used, and the respective specific gravities were:

Grade of Asphalt Cement		Specific Gravity	
Oil Asphalt OA-55	(50-60 penetration)	1.016	
Oil Asphalt OA-90	(85-100 penetration)	1.021	(sheet asphalt mixtures)
		1.004	(asphaltic concrete mixtures)
Oil Asphalt OA-135	(120-150 penetration)	1.010	
Oil Asphalt OA-230	(210-250 penetration)	1.011	

The RC-2 cut-back asphalt used in the preparation of the cut-back asphaltic concrete mixtures was obtained from the Talco Refinery of the American Republic Oil Company. The material conformed to the specifications of the Texas Highway Department. The distillation residue at 680°F. was determined in accordance with AASHO T 28-49 "Distillation of Cut-Back Asphaltic Products." The amount of residue was found to be 77.5 per cent by weight and the specific gravity of the residue was found to be 1.025.

Four groups of mixtures were tested. The first group consisted of seven series of sheet asphalt mixtures prepared in the laboratory and conforming to Texas Highway Department Specifications S-317 "Hot-Mix Asphaltic Concrete Pavement Type E." The second group consisted of 22 series (16 mixtures) of laboratory hot-mix asphaltic concrete mixtures conforming to Texas Highway Department Specification S-317 "Hot-Mix Asphaltic Concrete, Type D." The third group consisted of five series (three mixtures) of cut-back asphaltic concrete mixtures conforming to Texas Highway Department Specification S-309 "Cut-Back Asphaltic Concrete, Type M." The fourth group consisted of 10 series (five mixtures) of asphaltic concrete mixtures furnished by the Texas Highway Department from actual highway construction projects. All of the mixtures in the fourth group conformed to Texas Highway Department Specification S-317. Three of them were Type "D" and two Type "C." The mixtures of group four were sampled at the paving plant, and approximately 200 pounds of the complete mixture as taken from the mixed batches was furnished to the laboratory for testing.

The compositions of the mixtures for each of the groups are shown in Tables 2, 3, 4, and 5 along with the governing specifications.

TABLE 2

COMPOSITION OF SHEET ASPHALT MIXTURES CONFORMING TO TEXAS HIGHWAY DEPARTMENT SPECIFICATION S-317 "HOT-MIX ASPHALTIC CONCRETE PAVEMENT, TYPE E"

Composition of Mixtures

	PER CENT BY WEIGHT						
	Series A	Series B	Series C	Series D	Series E	Series K	Series L
Sand A	40.0	40.0	37.5	35.5	38.5	—	—
Limestone screenings	—	—	—	—	—	51.75	52.9
Sand B	40.0	40.0	37.5	35.5	38.5	36.0	36.8
Filler (limestone dust passing no. 200 sieve)	10.0	—	—	—	—	2.25	2.3
Filler (Portland Cement)	—	10.0	15.0	20.0	15.0	—	—
Asphalt cement (OA90)	10.0	10.0	10.0	9.0	8.0	10.0	8.0

Specifications and Grading of Total Aggregate

	Specification	Series A	Series B	Series C	Series D	Series E	Series K	Series L
Pass 10 ret'd. 40	15-40	23.9	23.9	22.4	21.0	22.5	32.2	32.2
Pass 40 ret'd. 80	20-45	35.6	35.6	33.4	31.3	33.6	23.9	23.9
Pass 80 ret'd. 200	12-32	27.9	28.0	26.4	24.7	26.5	28.9	28.9
Pass 200	10-20	12.6	12.5	17.8	23.0	17.4	15.0	15.0

The specification requires that the asphaltic material shall form from 7.5 to 12% of the mixture by weight.

TABLE 3

COMPOSITION OF FINE GRADED HOT-MIX ASPHALTIC CONCRETE MIXTURES CONFORMING TO TEXAS HIGHWAY DEPARTMENT SPECIFICATION S-317, HOT-MIX ASPHALTIC CONCRETE PAVEMENT, TYPE "D"

Composition of Aggregates

	PER CENT BY WEIGHT			
	Series AD, BD CD, DD	Series FG, GD HD, ID	Series KD, LD MD, ND	Series PD, QD RD, SD
Crushed limestone, ⅝"-¼"	25	30	—	—
Crushed limestone, ¼"-no. 10	25	30	—	—
Washed river gravel	—	—	58	60
Limestone screenings	25	—	26	—
Sand "A"	—	20	—	20
Sand "B"	25	15	16	15
Limestone dust (passing no. 200 sieve)	—	5	—	5

Specifications and Grading of Total Aggregate

	PER CENT BY WEIGHT				
	Specification	Series AD, BD CD, DD	Series FG, GD HD, ID	Series KD, LD MD, ND	Series PD, QD RD, SD
Pass ⅝" screen	100	100	100	100	100
Pass ½" screen	97-100	99.1	98.9	100	100
Pass ½" screen ret'd. ¼" screen	25-50	26.3	31.6	26.8	27.6
Pass ¼" screen ret'd. no. 10 sieve	15-35	30.1	23.8	28.9	26.6
Total ret'd. on no. 10 sieve	50-60	57.3	56.5	55.7	54.2
Pass no. 10 ret'd. no. 40	0-25	15.3	14.0	17.7	15.6
Pass no. 40 ret'd. no. 80	5-25	12.8	14.3	9.9	14.8
Pass no. 80 ret'd. no. 200	5-25	16.6	9.7	11.7	8.8
Pass no. 200	2-10	5.1	5.5	5.0	5.5

Type and Quantity of Asphaltic Material

Grade of Asphalt Cement	Series	Quantity Per Cent By Weight	Series	Quantity Per Cent By Weight	Series	Quantity Per Cent By Weight	Series	Quantity Per Cent By Weight
OA 90	AD	4.5	FD	4.5	KD	4.5	PD	4.5
	AD_T	4.5			KD_T	4.5		
	BD	5.25	GD	5.25	LD	5.25	QD	5.25
	BD_T	5.25						
	CD	6.0	HD	6.0	MD	6.0	RD	6.0
	CD_T	6.0						
	DD	6.75	ID	6.75	ND	4.0	SD	4.0
					ND_T	4.0		
OA 55	CD_3	6.0		—	LD_3	5.25	—	
OA 135	CD_4	6.0		—	LD_4	5.25	—	
OA 230	CD_2	6.0		—	LD_2	5.25	—	

The specification requires that the asphaltic material shall form from 4 to 7.5% of the mixture by weight.

TABLE 4

COMPOSITION OF CUT-BACK ASPHALTIC CONCRETE PAVING MIXTURES CONFORMING TO TEXAS HIGHWAY DEPARTMENT SPECIFICATION S-309, TYPE "M", FINE GRADED SURFACE COURSE

Composition of Mixtures

	SERIES			
	Aggregate Only All Mixtures	Total Mixture Per Cent by Weight		
		BM BM_M	DM	EM EM_M
Crushed limestone, ¾-¼	35	32.9	32.73	33.07
Crushed limestone, ¼-10	35	32.9	32.73	33.07
Sand "A"	15	14.1	14.02	14.18
Sand "B"	15	14.1	14.02	14.18
RC-2	—	6.0	6.5	5.5

Specification and Grading of Aggregates

	Specification	Grading (All Mixtures)
Passing ⅝" screen	100	100
Passing ½" screen	97-100	98.8
Passing ½" screen, retained on ¼" screen	30-60	36.8
Passing ¼" screen, retained on no. 10 sieve	20-40	27.8
Passing no. 10 sieve, retained on no. 40 sieve	5-20	12.1
Passing no. 40 sieve, retained on no. 80 sieve	5-15	12.2
Passing no. 80 sieve	5-15	9.8

The specification requires that the cut-back asphalt form from 5 to 7% of the mixture by weight.

TABLE 5

COMPOSITION OF FIVE MIXTURES FROM TEXAS HIGHWAY DEPARTMENT CONSTRUCTION PROJECTS CONFORMING TO TEXAS HIGHWAY DEPARTMENT SPECIFICATION S-317, TYPE "D" AND TYPE "C"

Type "D" Mixtures (Gradings Shown Are for Field Extraction)

	Specifications	Series SB	Series SG	Series SU
Pass ⅝" screen, ret'd. ½" screen	0-3	1.4	2.2	0.5
Pass ½" screen, ret'd. ¼" screen	25-50	35.4	31.6	26.5
Pass ¼" screen, ret'd. no. 10 sieve	15-35	15.2	21.0	22.4
Total retained on no. 10 sieve	50-60	52.0	54.8	49.4
Pass no. 10 sieve, ret'd. no. 40 sieve	0-25	12.2	17.3	16.5
Pass no. 40 sieve, ret'd. no. 80 sieve	5-25	16.7	13.2	18.4
Pass no. 80 sieve, ret'd. no. 200 sieve	5-25	11.1	6.0	5.8
Pass no. 200 sieve	2-10	3.6	3.8	5.3
Asphalt cement	4.0 to 7.5	4.4	4.9	4.6
Grade asphalt cement		OA-90	OA-230	OA-230

Type "C" Mixtures (Gradings Shown Are for Field Extraction)

	Specifications	Series SP	Series SC
Pass 1" screen, ret'd. ¾" screen, per cent	0-3	1.0	0.5
Pass ¾" screen, ret'd. ½" screen, per cent	15-40	17.0	19.5
Pass ½" screen, ret'd. ¼" screen, per cent	15-40	23.2	22.4
Pass ¼" screen, ret'd. no. 10 sieve	10-30	14.7	17.1
Total retained on no. 10 sieve, per cent	50-65	55.9	59.5
Pass no. 10 sieve, ret'd. no. 40 sieve, per cent	0-25	14.8	11.2
Pass no. 40 sieve, ret'd. no. 80 sieve, per cent	5-25	11.9	10.4
Pass no. 80 sieve, ret'd. no. 200 sieve, per cent	5-25	8.8	7.7
Pass no. 200 sieve	1-10	4.6	5.1
Asphalt cement	3.5-7	4.0	6.1
Grade asphalt cement		OA-90	OA-135

PREPARATION OF SPECIMENS AND DETERMINATION OF DENSITY

Three compaction procedures, the Marshall compaction procedure, the Texas Highway Department compaction procedure, and the Asphalt Institute compaction procedure were used in preparing the specimens. The details of proportioning, mixing, and compaction of the specimens are given in the following pages.

Sheet Asphalt Specimens and Hot-Mix Asphaltic Concrete Specimens

Marshall Compaction Procedure—The procedure used in preparation of the specimens by the Marshall method is given in "The Marshall Method for the Design and Control of Bituminous Paving Mixtures, Third Revision, February 1949."

1. The separate aggregates were dried and the quantities, to the nearest gram, required for a 1200-gram batch, were

weighed into tared aluminum pans. The aggregates were thoroughly mixed with a small trowel.

2. The pans were then placed in a 350°F. oven and left for a minimum of four hours. Just prior to mixing of a set of specimens, the asphalt cement was heated in a separate container to 350°F.

3. The aggregates were placed in the previously heated mixing bowl of a Hobart C-10 mixer and the proper quantity of hot asphalt cement was weighed into the bowl. The materials were then thoroughly mixed with the C-10 mixer for two minutes. Figure 1 shows the Hobart C-10 mixer, the mixing bowls, and the wire whip which were used in preparing the laboratory hot-mix asphaltic concrete specimens tested in this project.

4. The proper quantity of mixture to produce a specimen 2½ inches high was weighed into the tared and heated Marshall

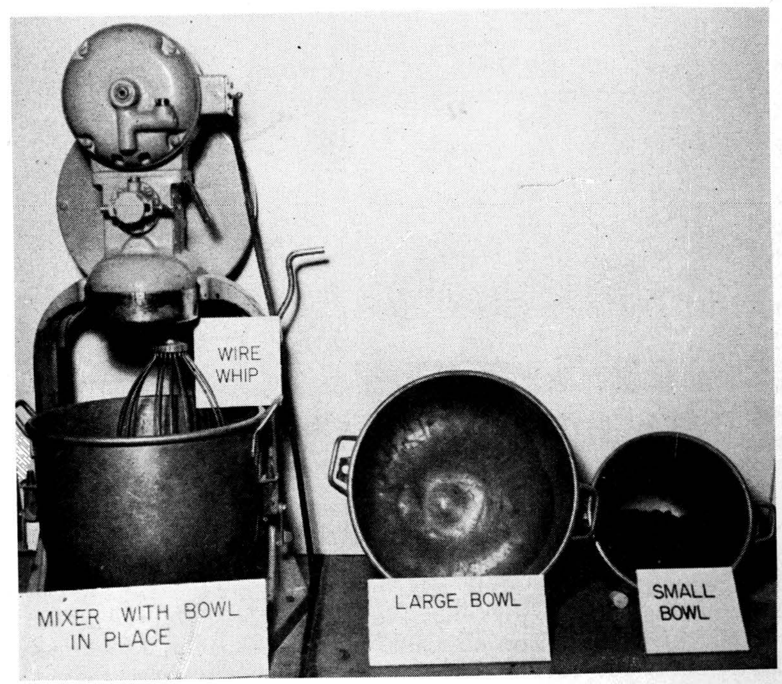


Figure 1. Mixing device used in the preparation of the laboratory hot mix asphaltic concrete specimens. During mixing the materials were continuously loosened from the side of the bowl with a spatula.

compaction mold and rodded with a trowel to eliminate segregation as much as possible.

5. The specimen was then compacted by applying 50 blows to one face with the compaction hammer. The mold was then inverted and 50 blows were applied to the opposite face.

6. The mold and specimen were placed in a bucket of water for a few minutes after which the specimen was removed from the mold and properly marked. Figure 2 shows the Marshall compaction mold and hammer and a specimen being compacted.

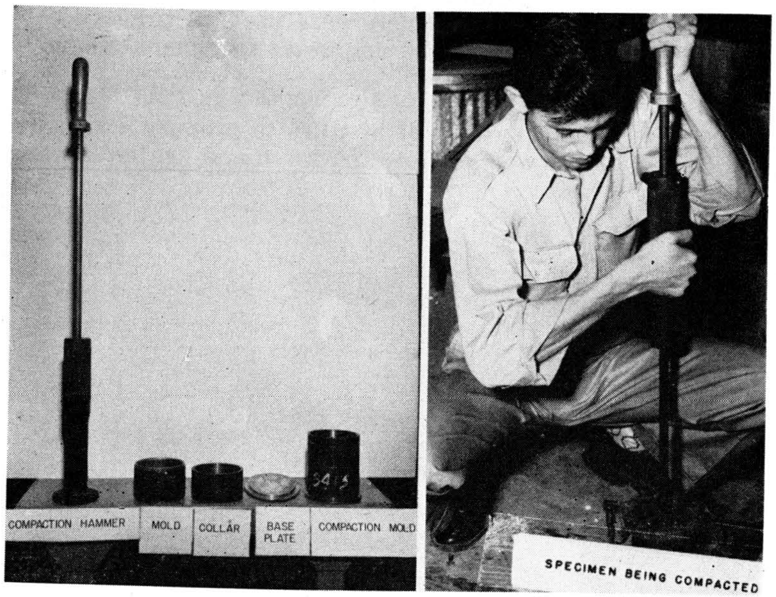


Figure 2. Apparatus used for Marshall compaction procedure and picture of specimen being compacted.

The asphaltic concrete mixtures of the fourth group received from the Texas Highway Department were in the mixed condition and their use violates the standard Marshall procedure which requires that mixtures shall not be reheated. It does not seem probable, however, that the re-heating would render the information obtained from the specimens valueless, particularly for correlation and comparison purposes.

The cold materials received from the construction projects were compacted in the following manner.

1. The asphaltic concrete mixture was heated in a 212°F. oven until it could be broken down easily. The mixture was then thoroughly broken down, mixed with a trowel and the proper quantity to produce a 2½-inch specimen was weighed into tared pans.

2. The mixture was then heated rapidly in the pans to a temperature (after thorough stirring) of 250°F. It was placed in the Marshall compaction mold and rodded with a trowel.

3. Compaction was accomplished in exactly the same manner as for steps 5 and 6 of the previous procedure.

Texas Highway Department Compaction Procedure—The compaction procedure used by the Texas Highway Department is given in Texas Highway Department Construction Bulletin C-14,[9] Part I "The Design of Asphaltic Concrete Paving Mixtures." The procedure used in this investigation was the same except for minor changes necessary because of the use of machine mixing.

1. The dried aggregates for a 1200-gram batch were weighed into tared mixing pans in the proper quantity, thoroughly mixed with a trowel, and placed in an oven at 350°F. for a minimum of four hours.

2. Just prior to preparation of a set of specimens, the asphalt was heated to 250°F. in a separate container. The aggregates were then placed in the tared mixing bowl of the Hobart C-10 mixer, and the proper quantity of asphalt was added. The materials were then mixed for a period of two minutes with the Hobart mixer.

3. The proper quantity of the mixture to produce a specimen 2½ inches high was then placed in the Texas Highway Department compaction mold in layers and pressed down. The temperature of the mixture at this time was about 250°F.

4. The mold was then placed in the press and the jack raised until a load of 50 pounds per square inch was indicated. A gyratory motion was then applied to the molding cylinder and to make three complete revolutions. The molding cylinder was then seated squarely on the lower guide ring. The process of applying a load of 50 pounds per square inch and imparting gyratory motion was repeated until a single jack stroke would increase the pressure 100 pounds per square inch. The molding

assembly and the press used in the Texas Highway Department compaction procedure are shown in Figure 3. Figure 3 also shows a specimen being subjected to the gyratory motion.

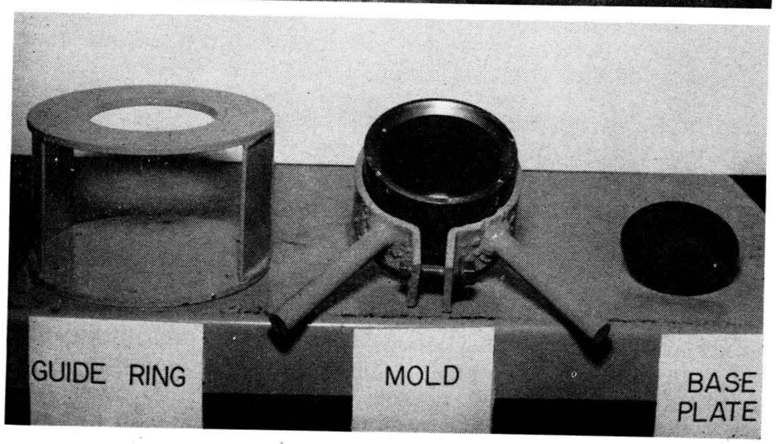


Figure 3. Specimen being compacted by Texas Highway Department procedure and picture showing details of mold.

5. A load of 2500 pounds per square inch gauge pressure was then applied and released.

6. The specimen was removed from the molding cylinder and properly marked.

The asphaltic concrete mixtures received from the Texas Highway Department in the mixed condition were molded as follows:

1. The mixture was heated in a 212°F. oven, thoroughly mixed and the proper quantity to produce a specimen 2½ inches high was weighed into tared pans.

2. The mixture was then heated rapidly to a temperature of 250°F. It was stirred thoroughly during heating.

3. The mixture was then placed in the compaction mold and the specimen was molded in exactly the same manner as stated in paragraphs four, five, and six of the procedure as previously given.

The Asphalt Institute Compaction Procedure—The compaction procedure given on pages 30 to 34 of the Asphalt Institute's "Manual on Hot-Mix Asphaltic Concrete Paving" was used with minor modifications made necessary by the use of machine mixing.

1. The dried aggregates were weighed into tared mixing pans in the proper quantities to produce a 3000-gram batch. The aggregates were then thoroughly mixed and placed in a 350°F. oven for a minimum of four hours. Just prior to preparation of a set of specimens, the asphalt was heated in a separate container to 250°F.

2. The hot aggregate was placed in the mixing bowl of the Hobart C-10 mixer, the proper quantity of asphalt was weighed into the bowl, and the materials were mixed for two minutes.

3. The mold was heated in a 212°F. oven prior to forming the specimens. About one-half of the material was placed in the mold and compacted with 30 blows of the No. 2 (1100 grams) tamper. The surface of this layer was scarified. The remainder of the mixture was placed in the mold and compacted with 30 blows of the No. 2 tamper followed by 30 blows with the No. 3 tamper. The molding cylinder was then inverted on the base plate. The specimen was forced to the bottom of the mold and compacted with 30 blows of the No. 2 tamper followed by 30 blows with the No. 3 tamper. The molding assembly was then placed in the testing machine and a load of 10,000 pounds applied with the plunger. This load

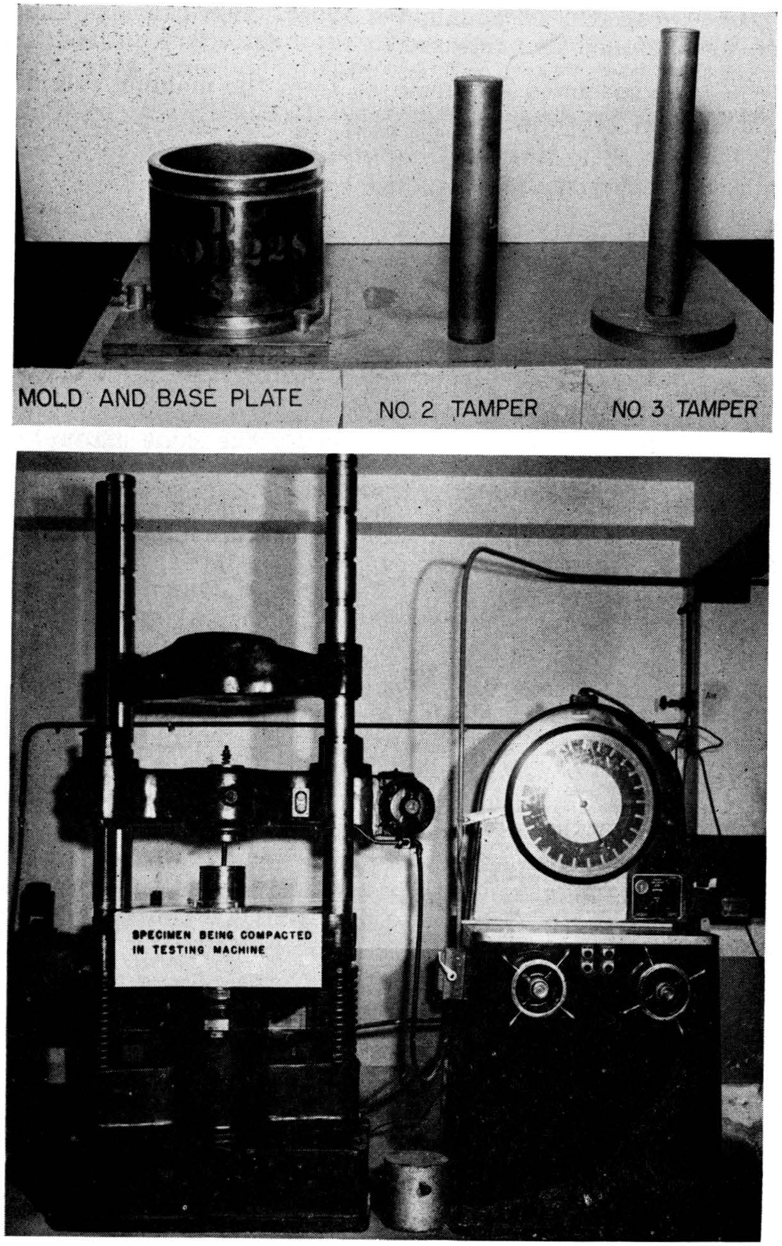


Figure 4. Mold and tampers for Asphalt Institute compaction procedure and specimen under compaction in testing machine.

was maintained for 15 minutes. Figure 4 shows the mold and tampers used in the Asphalt Institute procedure and also shows a specimen under load in the testing machine.

4. The specimen was then forced from the mold and proper identification was placed on the bottom of the sample.

For the prepared asphaltic concrete mixtures received from the Texas Highway Department the procedure was as follows:

1. The mixture was heated in 212°F. oven, broken down and thoroughly mixed. The 3000-gram batches were weighed into tared pans. Each batch was then heated as rapidly as possible to 250°F.

2. The mixture was compacted in accordance with the procedure shown in steps 3 and 4 preceding.

Cut-Back Asphaltic Concrete Mixtures

The cut-back asphaltic concrete or cold mix asphaltic concrete mixtures presented some difficulties from a compaction standpoint. Neither the Marshall method nor the Asphalt Institute method presents a procedure for the compaction of cut-back asphaltic concrete mixtures. The Texas Highway Department[9] procedure for cut-back asphaltic concrete mixtures was therefore modified and used when compacting by the Marshall method or Asphalt Institute method. A quantity of 3000 grams of total mixture was used for the Asphalt Institute method and the amount required to produce specimens 2½ inches high for the Marshall and Texas Highway Department methods. The exact procedures used were as follows.

1. The dry aggregates were weighed into a tared pan in amounts sufficient to produce the specimen. The RC-2 cutback asphalt was added in the proper quantity and the materials were mixed by hand with a trowel.

2. The pan and mixture were then placed in a 212°F. oven for 30 minutes. At the end of this period, the mixtures were removed from the oven and thoroughly mixed.

3. The pan and mixture were then returned to the 212°F. oven and left until it reached a constant weight. During this period the mixture was periodically stirred, weighed, and checked for constant weight. When the mixture reached constant weight it was removed from the oven and allowed

to cool. During the cooling period the mixture was stirred at intervals in order to maintain a uniform temperature throughout the mixture.

4. **Marshall compaction procedure.** When the mixture was cooled to 140°F. it was molded using exactly the same procedure as that given in steps 4, 5, and 6 of the Marshall compaction procedure for hot-mix asphaltic concrete.

The procedure used in compacting these specimens by the Marshall method was not considered to be entirely satisfactory in that proper density was not obtained in the specimens. When studying the results of the stability tests on the cut-back asphaltic concrete mixtures prepared by the Marshall method, this fact should be kept in mind.

5. **Texas Highway Department compaction procedure.** The cold mixture was cooled to 100°F. and molded in accordance with the same procedure as given in steps 4, 5, and 6 for the Texas Highway Department procedure for hot-mix asphaltic concrete.

6. **Asphalt Institute compaction procedure.** The cold mixture was cooled to 140°F. and molded in accordance with the same procedure as given in steps 3 and 4 for the Asphalt Institute procedure for hot-mix asphaltic concrete.

This procedure, while it was the best of several tried, did not produce specimens of the quality desired for determination of the stability by the Asphalt Institute method. Results of stability tests made on the specimens were quite erratic and are not shown in the following pages.

The problem of adapting the Marshall compaction procedure and the Asphalt Institute compaction procedure to the compaction of cut-back asphaltic concrete mixtures was not satisfactorily solved in this investigation. This problem warrants further study.

Determination of Specific Gravity

The specific gravity of all the specimens prepared was determined by using the same general procedure. The procedure used is essentially that recommended by the Texas Highway Department in Construction Bulletin C-14.[9]

1. A waxed thread was looped around the specimen. The specimen was then weighed in air to the nearest gram—weight A.

2. The specimen was dipped several times into paraffin held at a temperature of 2°F. to 4°F. above its melting point. The paraffin coated specimen was then allowed to cool and weighed in air to the nearest gram—weight B.

3. The specimen was then suspended completely in water on the waxed thread and weighed to the nearest gram—weight C.

4. The specific gravity was determined from the expression:

$$\text{Specific Gravity (d)} = \frac{A}{(B-C) - \left[\dfrac{(B-A)}{\text{Specific Gravity of Paraffin}}\right]}$$

5. The theoretical specific gravity was then calculated as follows:

$$\text{Theoretical Specific Gravity (D)} = \frac{100}{\Sigma\left(\dfrac{\text{Percentage by weight of component of mixture}}{\text{Specific gravity of component}}\right)}$$

For example the theoretical density of sheet asphalt mixture series A is calculated as follows (see Table 1 and Table 2):

$$D = \frac{100}{\dfrac{40}{2.624} + \dfrac{40}{2.622} + \dfrac{10}{2.725} + \dfrac{10}{1.021}} = 2.275$$

6. The percentage of voids is then obtained from the expression:

$$\text{Per cent voids} = \left(\frac{D-d}{D}\right) 100$$

THE STABILITY TEST PROCEDURES

It is common practice to perform the stability tests on asphaltic concrete mixtures at a temperature of 140°F. Practice varies with regard to the manner in which the 140°F. temperature is produced. Some standard procedures provide for obtaining the temperature by heating in a water bath, while other procedures require that the specimens be heated in air. All of the specimens for the stability tests conducted in this investigation were heated in a constant temperature oven held at 140°F. ± 1°F. for a period of at least four hours prior to testing. In all cases the specimens were tested as

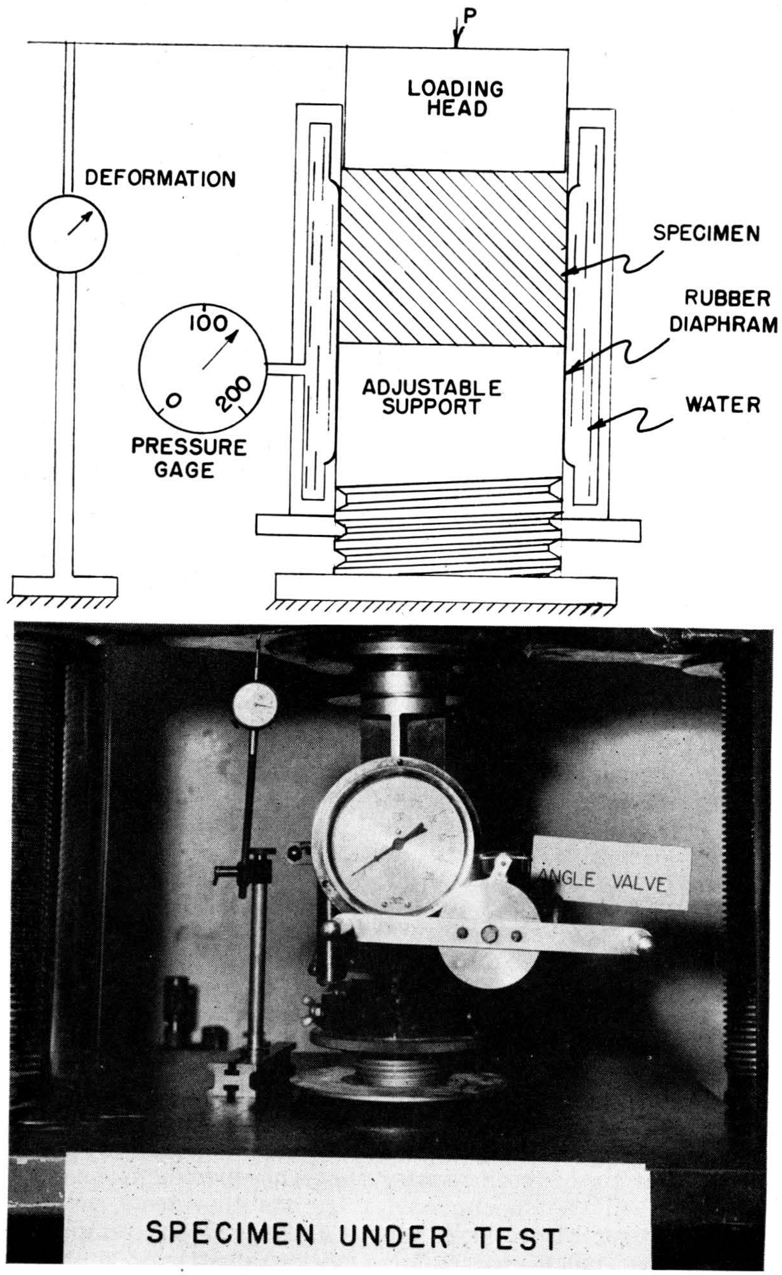


Figure 5. The Hveem stability test.

rapidly as possible after removal from the oven in order to avoid loss of heat.

Hveem Stability Test

In the Hveem stability test the specimen is tested in a closed system. An increasing vertical pressure is applied to the 4-inch diameter faces of the specimens and the lateral pressure transmitted through a rubber diaphragm in which the specimen is held is measured. Figure 5 shows the details of the test schematically and a view of the stabilometer in the testing machine during an actual test.

The detailed test procedure used in performing the test was that of the Texas Highway Department, the essential features of which are:

1. The initial displacement of the stabilometer was adjusted to a value between .070 and .080.

2. The specimen to be tested was removed from the 140°F. oven and a serrated skirt of 2½-inch gummed tape was placed around the specimen. The paper skirt was necessary to protect the rubber diaphragm from injury due to sharp aggregates in the specimens. The lower plate of the stabilometer was set to conform to the height of the specimen.

3. A 4-inch paper disc was placed over the lower head. The specimen was placed on the disc and the body of the stabilometer was lowered over the specimen. The initial lateral pressure of five pounds per square inch was then applied with the pump after which the angle valve was closed. A second paper disc was placed over the specimen.

4. The specimen was placed in the testing machine and the loading head was brought into position for loading. The deflection measuring device was adjusted into position for reading the vertical movements of the specimen during testing. The load was applied at a rate of .05 inches per minute movement.

5. Readings of the lateral pressure and of the vertical movement were made at vertical loads of 500, 1000, 1500, 2500, and 3000 pounds and at each 1000 pounds of vertical load thereafter. The vertical load corresponding to a lateral pressure of 200 pounds per square inch was also determined.

6. The vertical load was reduced to 1000 pounds, the angle valve was opened, and the final displacement measurement was made.

Figure 6 shows a typical set of data obtained from the test of a specimen. Five specimens of each of the individual mixtures were tested.

ASPHALTIC CONCRETE RESEARCH
HVEEM STABILOMETER TEST

Design No.	Asphaltic Concrete	**Date**	
Spec. No.	BD-16	**By**	
Ht. Spec.	2.49 inches	**Initial Displ.**	0.074
		Final Displ.	0.136

Remarks:

VERTICAL LOAD (LB.)	HVEEM GAUGE (LB.)	VERTICAL AMES (IN.)	VERTICAL LOAD (LB.)	HVEEM GAUGE (LB.)	VERTICAL AMES (IN.)
	5		11,000	132	.047
100		0.000	12,000	155	.051
500	6	.003	13,000	196	.057
1,000	8	.007	14,000		
1,500	10	.009	15,000		
2,000	12	.011	16,000		
2,500	15	.013	17,000		
3,000	18	.015	18,000		
4,000	25	.020	19,000		
5,000*	37	.024	20,000		
6,000	46	.028	21,000		
7,000	59	.032	22,000		
8,000	75	.036	23,000		
9,000	92	.040	24,000		
10,000	110	.044			

Hveem % Stability (For 2-5/16″ Ht. Spec.) = 61.5
Hveem % Stability (Corrected to 2.5″ Ht.) = 64.7
*Critical Pressure for determining Hveem Stability.

Figure 6. Typical set of data for Hveem stability test.

The stability value for each specimen was computed by means of the emperical formula:

$$S = \cfrac{22.2}{\cfrac{RD}{400 - R} + .222}$$

Where S is the relative stability,

R is the stabilometer gauge reading at 400 pounds per square inch applied load (5000 pounds total load), and

D is the number of turns displacement of the specimen (one turn is equivalent to one revolution of the Ames dial or 0.1 inch indicated movement).

Further interpretation of the test results was also made using the method recommended by L. E. McCarty in his paper "Applications of the Mohr Circle and Stress Triangle Diagrams

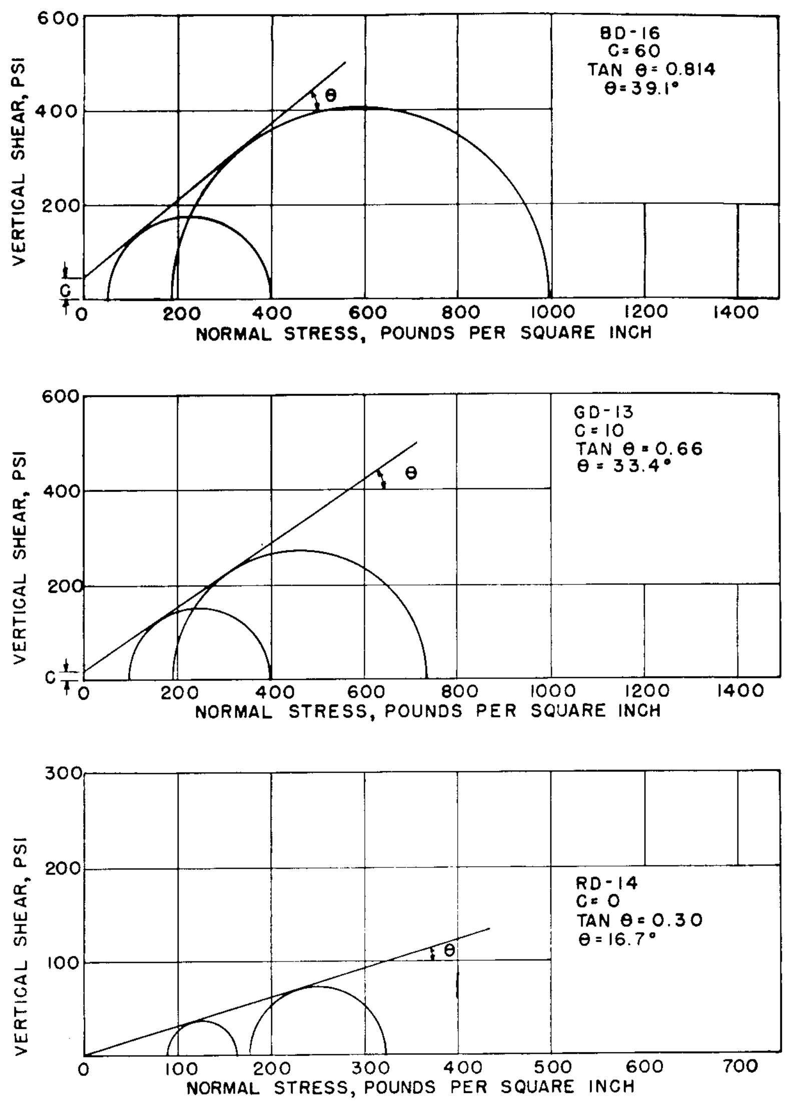


Figure 7. Typical Mohr circles obtained by plotting vertical and lateral pressures from the Hveem stability test.

to Test Data Taken with the Hveem Stabilometer." The Mohr circles were plotted for each vertical unit pressure and the corresponding lateral pressure. A line was then drawn tangent to the circle at 400 pounds per square inch vertical pressure and to the circle at 200 pounds per square inch lateral pressure. For specimens in which the maximum vertical pressure was below or not much in excess of 400 pounds per square inch (5000 pounds vertical load) the best average line tangent to the stress circles was drawn. The angle of internal friction was taken as the slope of the line, and its intercept on the shear stress axis as the unit cohesive strength. A typical set of these curves with the tangent lines drawn appears in Figure 7.

For each mixture the results of the five tests were averaged. Values which were obviously in error were thrown out. The results obtained from the tests were: Hveem stability value, per cent; angle of internal friction, degrees; and cohesive strength, pounds per square inch.

Marshall Stability Test

In the Marshall stability test the 4-inch diameter specimens are loaded along the perimeter of the specimen through two circular loading heads. The load is applied at the rate of 2.0 inches per minute. As the specimen is compressed the vertical movement is measured. The loading method is shown schematically in Figure 8 along with a view of a specimen in the machine ready for testing. The procedure used in performing the test was as follows:

1. The loading heads were heated to 140°F. in the constant temperature oven.

2. The specimen to be tested was taken from the oven and placed in the loading heads. The heads were placed in the stability machine in position for testing. The Ames dial reading flow (vertical movement) was set at zero.

3. The load was applied at the rate of 2.0 inches per minute. The maximum load and the vertical movement at maximum load were read and recorded.

Five specimens were tested for each mixture. The results were averaged, discarding the values for those specimens which were obviously in error. The Results obtained from the test were: (1) stability value (maximum load) in pounds, and (2) flow (vertical deformation at maximum load) in inches.

Texas Highway Department Punching Shear

For a number of years the Texas Highway Department used a punching shear test to measure the stability of asphaltic

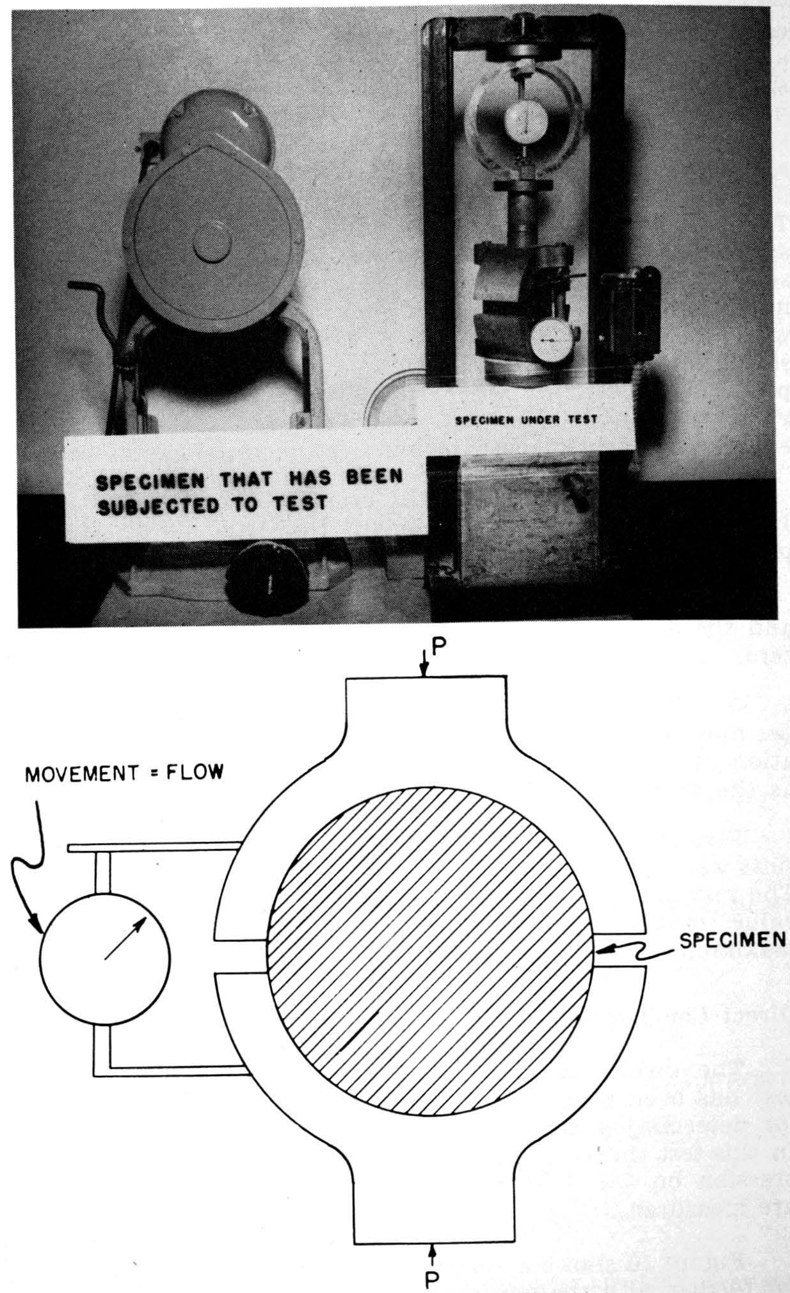


Figure 8. The Marshall stability test.

concrete specimens. The test consisted of applying a load over a 1-inch circular area on one 4-inch specimen face with the specimen being supported on the perimeter of a 3-inch diameter circle on the opposite face. The specimen was laterally supported by a brass ring in which it was tested. The test results in shearing out a frustrum of a cone with a top diameter of one inch and a bottom diameter of three inches. The procedure followed in this work was not exactly the same as that used by the Texas Highway Department. The lateral support furnished by the brass ring was eliminated thus making the test an unconfined shear test. The rate of loading was also changed to conform to that used for the Marshall stability test, 2.0 inches per minute. The details of the loading procedure are shown schematically in Figure 9, along with a view of a specimen in the machine ready for testing. The exact procedure followed in making the tests was as follows:

1. The testing device was brought to a temperature of 140°F. The specimen was removed from the 140°F. oven and placed on the testing machine platform for testing.

2. An initial load of 10 pounds was placed on the specimen and the device for measuring vertical deformation was set at zero.

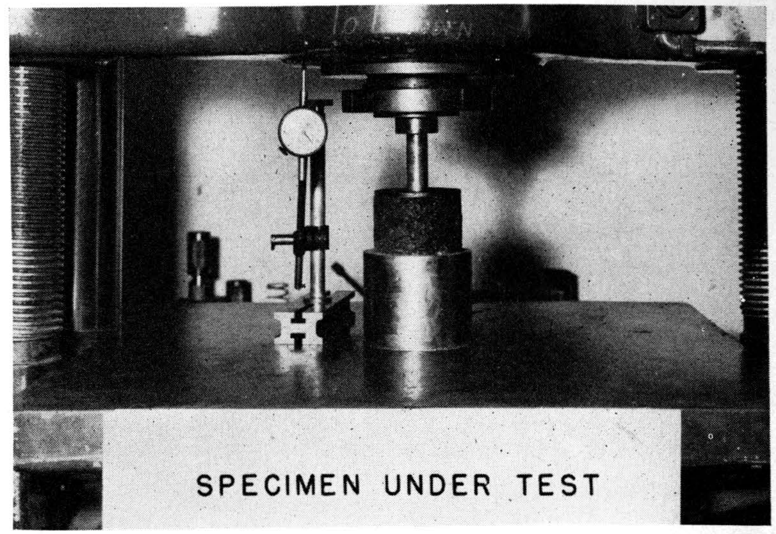
3. The specimen was then loaded at the rate of 2.0 inches per minute. The maximum load was recorded and the deformation at the maximum load. The maximum load was taken as the stability value.

Five specimens were tested for each mixture and the results were averaged (discarding the values obviously in error). The results reported for this stability test are: (1) the stability value (maximum load) in pounds and (2) the deformation at maximum load in inches.

Direct Compression Test

The direct compression test or unconfined compression test has been proposed and used as a suitable test procedure for determining the stability of asphaltic concrete mixtures. In this test the 4-inch diameter specimens are loaded in compression on the 4-inch faces and the vertical deformations are measured.

Figure 10 shows a specimen in the testing machine ready for testing with the device for measuring the vertical deform-



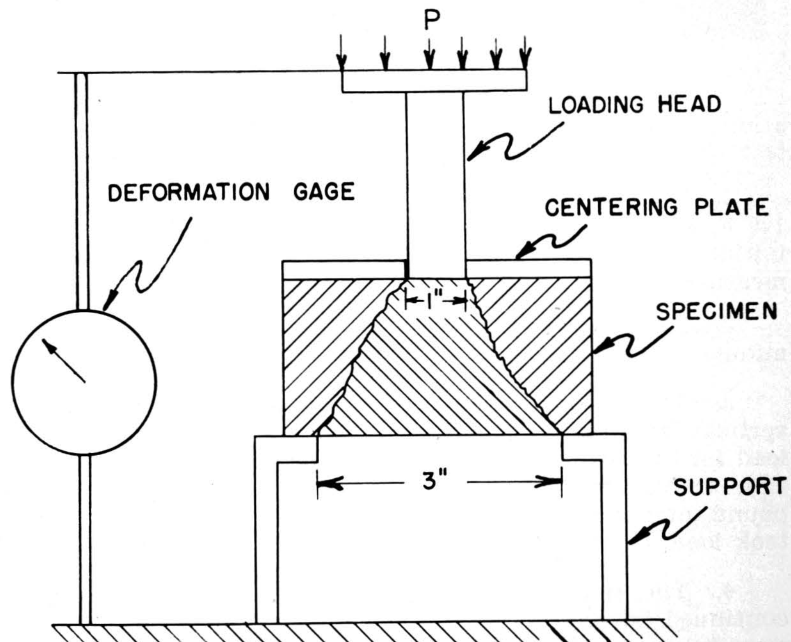


Figure 9. Modified Texas Highway Department punching shear stability test.

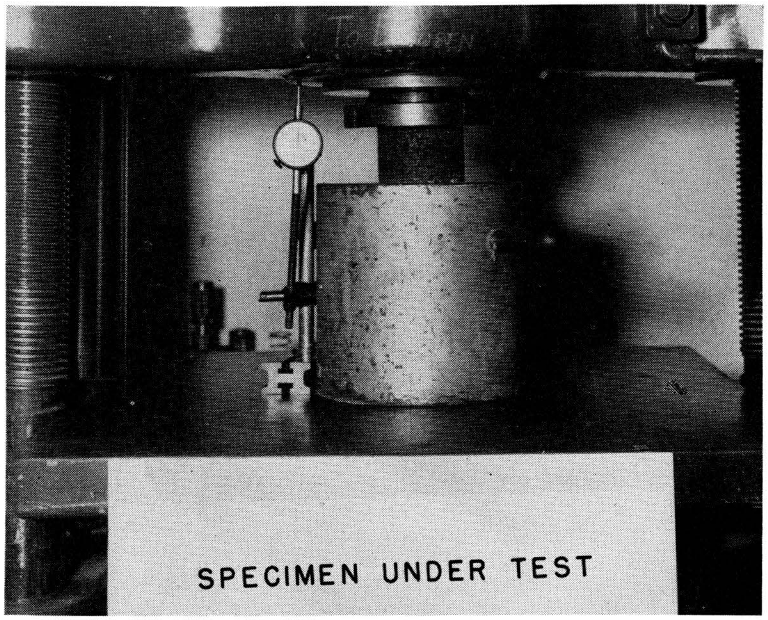


Figure 10. Details of direct compression test.

ation in place. The specific steps taken in performing the test were:

1. The specimen, immediately upon removal from the 140°F. oven, was centered in the testing machine and an initial vertical load of 10 pounds applied. The deformation measuring device was set at zero.

2. The load was applied at the rate of .05 inches per minute.

3. The initial deformation reading was taken at 50 pounds vertical load for weak mixtures and at 100 pounds vertical load for the stronger materials. Readings of vertical deformation thereafter were taken at 50 pound, 100 pound, or 200 pound intervals depending upon the rate at which the material took load.

4. The maximum load was determined. Loading was continued beyond the maximum load and the load readings were taken for .020 or .025 inch increments of vertical movement until the vertical load dropped to about one-half of the maximum load.

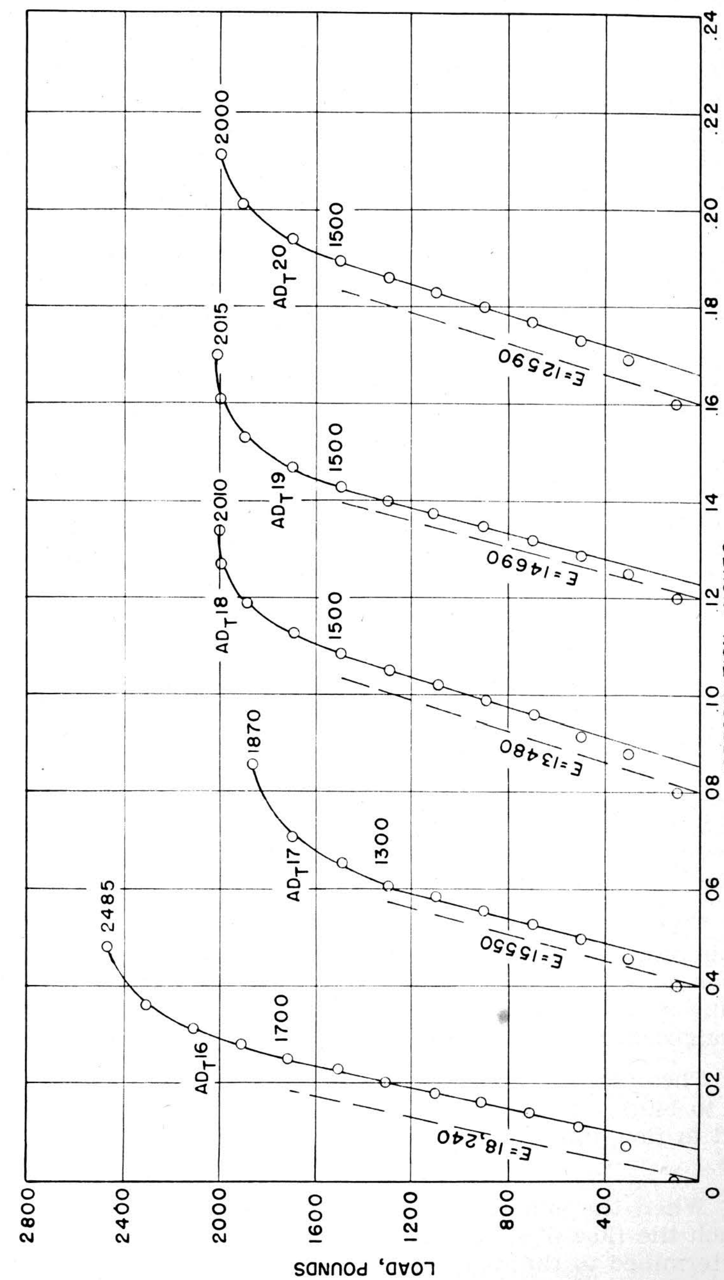


Figure 11. Typical load-deformation diagrams for asphaltic concrete mixtures.

Upon completion of the test, curves were plotted showing the relation between the load and the vertical deformation. A typical set of these curves is shown in Figure 11. From these curves, the proportional limit load was determined as the maximum load for which a linear relationship between load and deformation existed, see Figure 11. The modulus of elasticity was also determined for each specimen by correcting the straight line portion of the curve to make it pass through the origin and using the fundamental relationship: $E = \frac{Ph}{\triangle A}$

- E = modulus of elasticity, pounds per square inch.
- P = any load on corrected curve below the proportional limit, pounds.
- A = cross section area of specimen (12.56), square inches.
- $\triangle$ = vertical deformation corresponding to P, inches.
- h = height of specimen, inches.

Five specimens were tested and the results averaged. The following information resulted from the test:

Proportional limit, pounds.
Ultimate strength, pounds.
Modulus of elasticity, pounds per square inch.

Cohesiometer

In the cohesiometer test the 4-inch diameter specimen is loaded in cantilever bending. The load is applied at the end of a 30-inch moment arm by allowing shot to flow into a bucket attached to the moment arm. The manner of loading and a view of the specimen in the machine ready for loading are shown in Figure 12. The test was run as follows:

1. The specimen was removed from the 140°F. oven and placed in position on the table of the cohesiometer. A straightedge was placed across the top of the specimen and the lower adjusting nuts for the upper plates were run up snug against the straightedge. The upper heads were then put in place.

2. The temperature in the cohesiometer was allowed to return to 140°F. The loading arm was then released and shot allowed to flow into the bucket at the rate of 1800 grams per minute.

3. When the end of the loading arm had deflected one-half inch the flow of shot was stopped. The quantity of shot was determined to the nearest gram.

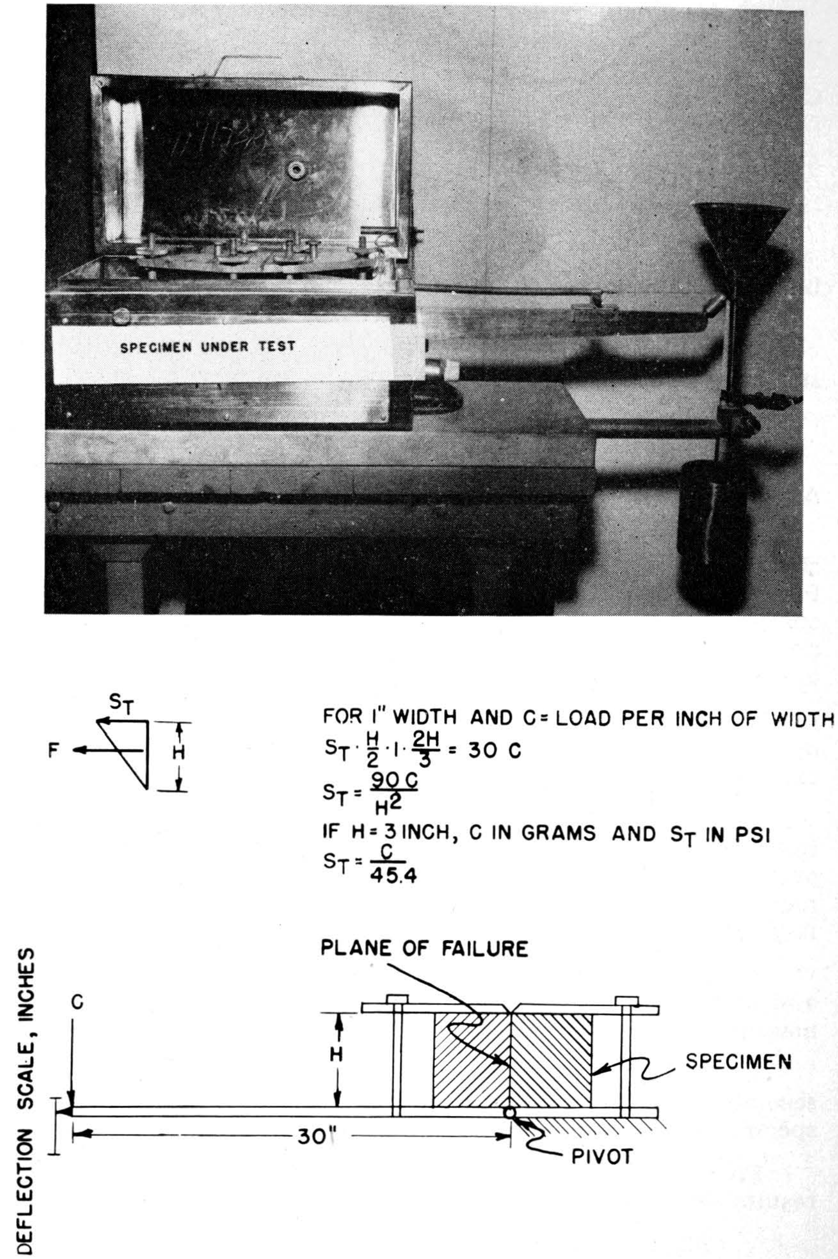


Figure 12. The cohesiometer test.

4. The load in grams was then converted to the load per inch for a 3-inch height by means of the equation:

$$C = \frac{L}{.80H + .178H^2}$$

C = load per inch corrected to 3-inch height, grams.
L = cohesiometer load at ½ inch deflection, grams.
H = height of specimen, inches.

5. The modulus of rupture (MR) in pounds per square inch, if desired can be obtained by the expression: $MR = \frac{C}{45.4}$

Five specimens of each mixture were tested in the cohesiometer. The following average results were obtained.

Load per inch corrected to 3-inch height, grams.

Asphalt Institute Stability Test

The Asphalt Institute stability test is of the punching shear type but differs from the Texas Highway Department Punching Shear Test as modified for this work in that the specimen is confined and the load is applied over an area greater than the area of the hole through which the specimen is extruded by failure in shear.

The manner of applying the load and a view of the stability device in the testing machine are shown in Figure 13. The exact details of the test procedure used were:

1. The testing ring was clamped to the bottom of the testing mold. The specimen was removed from the 140°F. oven and placed in the mold for testing. Slight pressure was required to seat the specimen in the mold. The original upper face was placed down.

2. The testing plunger was placed on top of the specimen and an initial load of 10 pounds was applied. The device for measuring deformation was set at zero.

3. The load was applied at a rate of one inch in 25 seconds. The maximum load and the deformation of the specimen at maximum load were determined.

Five specimens were tested for each mixture and the results were averaged and reported as:

Asphalt Institute Stability, pounds.
Deformation at Failure, inches.

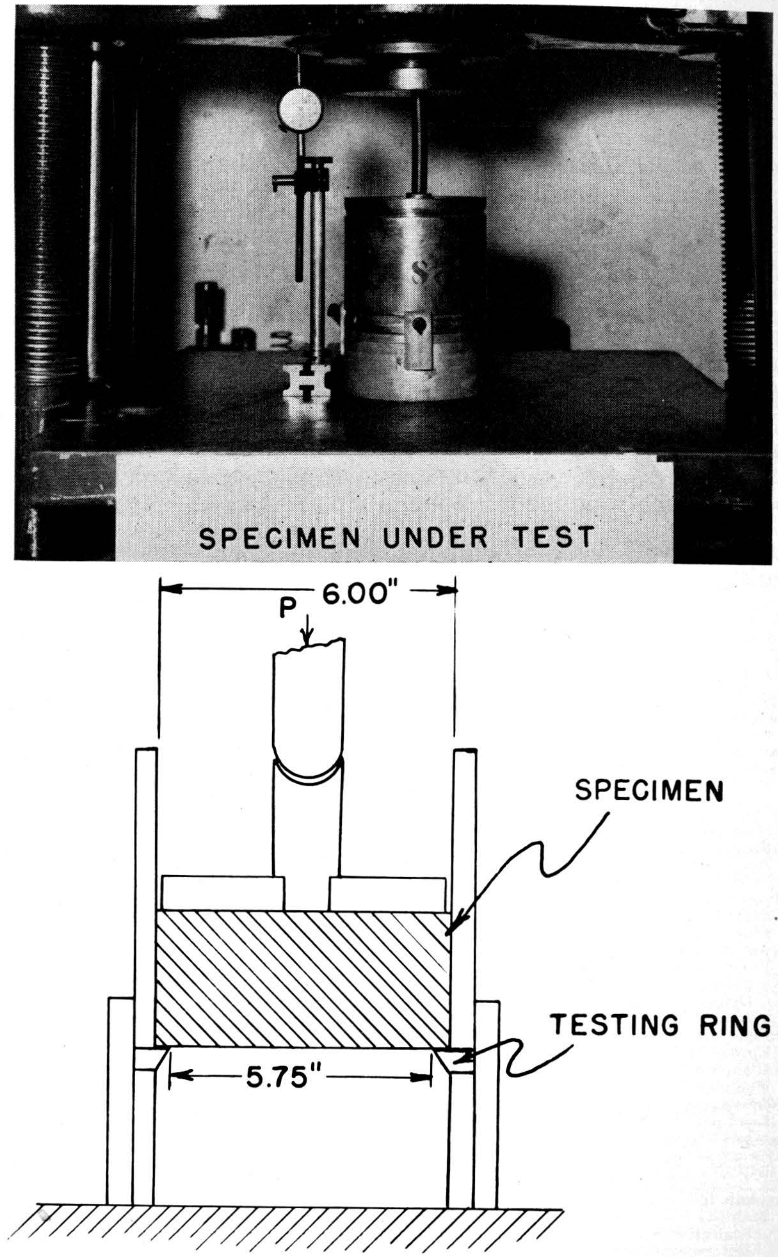


Figure 13. The Asphalt Institute stability test.

EXPERIMENTAL RESULTS

The mixtures selected for use in this investigation were designed to provide a wide range of stability characteristics. The exception to this statement is the group of five mixtures from actual construction projects of the Texas Highway Department which were designed to meet its specifications and to provide an adequate road surface for the vehicles using the highways.

Results of Tests on Laboratory Sheet Asphalt Mixtures

The 4-inch diameter specimens of sheet asphalt for the Hveem stability, Marshall stability, Texas Highway Department punching shear stability, direct compression, and cohesiometer tests were all molded by the Marshall compaction procedure. The 6-inch specimens for the Asphalt Institute stability test were molded by the Asphalt Institute compaction procedure. Five of the sheet asphalt mixtures, A, B, C, D, and E were composed of the rounded siliceous sands (A and B) with filler and

TABLE 6

RESULTS OF STABILITY TESTS ON SHEET ASPHALT PAVING MIXTURES

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT						
	Series A	Series B	Series C	Series D	Series E	Series K	Series L
Pass no. 10 sieve, ret'd. no. 200 sieve	78.7	78.7	74.0	70.1	76.0	76.5	78.2
Pass no. 200 sieve	11.3	11.3	16.0	20.9	16.0	13.5	13.8
Asphalt cement	10.0	10.0	10.0	9.0	8.0	10.0	8.0
	Results of Stability Tests, Marshall Compaction Procedure						
Hveem Stability:							
Stability, per cent	21.2	23.5	20.0	23.4	24.4	14.8	34.7
Angle internal friction, °	25.2	27.4	24.1	27.1	27.2	23.4	33.1
Marshall Stability:							
Stability, lb.	438	555	445	1078	469	1480	1220
Flow, in.	.15	.12	.155	.132	.098	.21	.115
Texas Highway Department Punching Shear:							
Stability, lb.	190	169	119	262	99	260	250
Deformation at failure, in.	.12	.13	.132	.125	.098	.138	.087
Direct Compression:							
Elastic limit, lb.	285	290	324	575	150	700	800
Ultimate strength, lb.	365	374	460	775	196	907	1015
Modulus of elasticity, psi.	1330	1230	1660	2840	763	2460	4510
Cohesiometer:							
Load per in., corrected to 3″ height, g.	89	88	123	149	77	171	154
Average voids, per cent	5.47	4.96	3.61	3.70	8.62	2.39	6.40
	Asphalt Institute Compaction Procedure						
Asphalt Institute Stability:							
Stability, lb.	930	830	575	940	1860	2750	3900
Deformation at failure, in.	.238	.121	.187	.184	.297	.560	.328
Average voids, per cent	5.34	6.81	5.55	4.01	6.65	10.25	11.02

asphalt cement and two of the sheet asphalt mixtures, K and L were composed of limestone screenings, siliceous sand, filler and asphalt cement. The exact composition of the mixture is shown in Table 2. The results of the tests on the sheet asphalt mixtures are shown in Table 6.

Results of Tests on Laboratory Hot-Mix Asphaltic Concrete Mixtures

The compositions of the laboratory hot-mix asphaltic concrete specimens tested in this project are shown in Table 3. The mixtures include four different aggregate combinations with four variations in asphalt content for each combination, a total of 16 mixtures. In addition two of the mixtures were prepared using three consistencies of asphalt other than the OA-90 used for the 16 mixtures. These 22 mixtures were mixed and 25 specimens were compacted by the Marshall compaction procedure and five specimens by the Asphalt Institute procedure for each mixture.

Five of the mixtures were also mixed and 25 specimens were prepared by the Texas Highway Department compaction procedure.

The results of the stability tests and of the void determinations on the 27 series of mixtures are shown in Tables 7 to 12 which follow. The series which are designated by the subscript T were compacted by the Texas Highway Department compaction procedure.

TABLE 7

RESULTS OF STABILITY TESTS ON HOT-MIX ASPHALTIC CONCRETE MIXTURES TEXAS HIGHWAY DEPARTMENT S-317—TYPE "D"

Coarse Aggregate—Crushed Limestone
Fine Aggregate—Limestone Screenings and Field Sand

Series AD, BD, CD, DD Marshall Compaction
Series AD_T, BD_T, CD_T Texas Highway Department Compaction

Aggregate Gradation Constant
Asphalt Cement OA-90, Variable

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT						
	Series AD	Series AD_T	Series BD	Series BD_T	Series CD	Series CD_T	Series DD
Crushed limestone, ½″ to no. 10	47.75	47.75	47.37	47.37	47.0	47.0	46.63
Limestone screenings	23.88	23.88	23.69	23.69	23.5	23.5	23.31
Sand "B", field sand	23.87	23.87	23.69	23.69	23.5	23.5	23.31
Asphalt cement, OA-90	4.5	4.5	5.25	5.25	6.0	6.0	6.75

	Results of Stability Tests						
Hveem Stability:							
Stability, per cent	55.4	57.0	58.4	24.0	54.6	11.0	35.6
Angle internal friction, °	40.4	38.6	38.9	24.5	37.9	19.1	35.2
Cohesion, psi.	36	34	44	10	40	0	18
Marshall Stability:							
Stability, lb.	1550	2020	1750	1860	1760	1895	1170
Flow, in.	.075	.133	.081	.145	.139	.146	.142
Texas Highway Department Punching Shear:							
Stability, lb.	208	283	395	354	334	342	253
Deformation at failure, in.	.068	.078	.080	.135	.132	.164	.093
Direct Compression:							
Elastic limit, lb.	1240	1500	1670	1680	1100	1420	650
Ultimate strength, lb.	1430	2080	2025	2350	1420	1770	900
Modulus of elasticity, psi.	8810	14950	10350	10350	7860	7820	4140
Cohesiometer:							
Load per in. corrected to 3″ height, g.	142	215	151	251	163	245	182
Average voids, per cent	7.03	3.13	6.43	.714	4.57	.15	2.79
	Asphalt Institute Compaction Procedure						
Asphalt Institute Stability:							
Stability, lb.	4720		6070		4180		3920
Deformation at failure, in.	.214		.222		.239		.276
Average voids, per cent	10.57		7.55		6.57		2.40

TABLE 8

RESULTS OF STABILITY TESTS ON HOT-MIX ASPHALTIC CONCRETE MIXTURES TEXAS HIGHWAY DEPARTMENT S-317—TYPE "D"

Coarse Aggregate—Crushed Limestone
Fine Aggregate—Limestone Screenings and Field Sand

Mixture Constant
Type of Asphalt Variable

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT			
	Series CD_3	Series CD	Series CD_1	Series CD_2
Crushed limestone, ½″ to no. 10	47.0	47.0	47.0	47.0
Limestone screenings	23.5	23.5	23.5	23.5
Sand B, field sand	23.5	23.5	23.5	23.5
Asphalt cement	6.0	6.0	6.0	6.0
Grade of asphalt cement	OA-55	OA-90	OA-135	OA-230
	Results of Stability Tests Marshall Compaction Procedure			
Hveem Stability:				
Stability, per cent	49.5	54.6	55.7	55.0
Angle internal friction, °	37.3	37.9	38.3	39.3
Cohesion, psi.	30	40	40	37
Marshall Stability:				
Stability, lb.	2430	1760	1530	645
Flow, in.	.107	.139	.080	.070
Texas Highway Department Punching Shear:				
Stability, lb.	591	334	333	71
Deformation at failure, in.	.105	.132	.088	.056
Direct Compression:				
Elastic limit, lb.	1400	1100	750	575
Ultimate strength, lb.	1870	1420	1035	690
Modulus of elasticity, psi.	6600	7860	5310	4990
Cohesiometer:				
Load per in. corrected to 3″ height, g.	307	162	132	60
Average voids, per cent	5.00	4.57	4.47	5.78

	Asphalt Institute Compaction Procedure			
Asphalt Institute Stability:				
Stability, lb.	4230	4180	3120	2790
Deformation of failure, in.	.235	.239	.263	.148
Average voids, per cent	7.53	6.57	5.57	5.67

TABLE 9

RESULTS OF STABILITY TESTS ON HOT-MIX ASPHALTIC CONCRETE MIXTURES TEXAS HIGHWAY DEPARTMENT S-317—TYPE "D"

Coarse Aggregate—Crushed Limestone
Fine Aggregate—Siliceous Sand

Aggregate Gradation Constant
Asphalt Cement OA-90 Variable

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT			
	Series FD	Series GD	Series HD	Series ID
Crushed limestone, ½″ to no. 10	57.30	56.85	56.4	55.95
Sand "A", concrete sand	19.10	18.95	18.8	18.65
Sand "B", field sand	14.33	14.21	14.1	13.99
Limestone dust	4.77	4.74	4.7	4.66
Asphalt cement, OA-90	4.50	5.25	6.0	6.75
	Results of Stability Tests, Marshall Compaction Procedure			
Hveem Stability:				
Stability value, per cent	40.0	37.0	24.0	0
Angle of internal friction, °	36.6	37.5	31.8	9.1
Cohesion, C, psi.	38	9	10	0
Marshall Stability:				
Stability value, lb.	1170	1260	1180	960
Flow, in.	.074	.121	.145	.283
Texas Highway Department Punching Shear:				
Stability value, lb.	194	214	213	229
Deformation at failure, in.	.071	.088	.108	.200
Direct Compression:				
Elastic limit, lb.	880	1250	520	570
Ultimate strength, lb.	1085	1670	750	780
Modulus of elasticity, psi.	7970	10230	3340	1810
Cohesiometer:				
Average load per in. corrected to 3″ height, g.	161	160	198	186
Average voids, per cent	7.51	3.08	2.20	1.670
	Asphalt Institute Compaction Procedure			
Asphalt Institute Stability:				
Average stability, lb.	2860	3530	4130	2780
Average deformation at failure, in.	.201	.175	.279	.320
Average voids, per cent	7.39	4.75	1.69	0.89

TABLE 10

RESULTS OF STABILITY TESTS ON HOT-MIX ASPHALTIC CONCRETE MIXTURES TEXAS HIGHWAY DEPARTMENT S-317—TYPE "D"

Coarse Aggregate—Siliceous Gravel
Fine Aggregate—Limestone Screenings and Field Sand

Aggregate Gradation Constant
Asphalt Cement OA-90 Variable

Series KD, LD, MD, ND Marshall Compaction Procedure
Series KD_T, ND_T, Texas Highway Department Compaction

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT					
	Series ND	Series ND_T	Series KD	Series KD_T	Series LD	Series MD
Washed river gravel	55.68	55.68	55.39	55.39	54.96	54.52
Limestone screenings	24.96	24.96	24.83	24.83	24.64	24.44
Sand "B", field sand	15.36	15.36	15.28	15.28	15.16	15.04
Asphalt cement OA-90	4.00	4.00	4.50	4.50	5.25	6.00
	Results of Stability Tests					
Hveem Stability:						
Stability, per cent	37.6	46.8	37.7	29.0	40.0	22.0
Angle internal friction, °	34.0	34.9	34.8	27.6	34.3	23.9
Cohesion, C, psi.	29	28	23	8	32	13
Marshall Stability:						
Stability, lb.	1040	1370	1200	1350	1005	915
Flow, in.	.075	.119	.085	.152	.154	.179
Texas Highway Department Punching Shear:						
Stability, lb.	260	305	274	290	320	260
Deformation at failure, in.	.080	.095	.092	.119	.085	.107
Direct Compression:						
Elastic limit, lb.	585	1050	780	820	630	530
Ultimate strength, lb.	740	1440	1205	1150	870	720
Modulus of elasticity, psi.	6750	8860	5820	5810	4580	2660
Cohesiometer:						
Load per in. corrected to 3" height, g.	145	156	201	253	213	239
Average voids, per cent	7.61	2.66	6.09	.68	3.36	2.05
	Asphalt Institute Compaction Procedure					
Asphalt Institute Stability:						
Stability, lb.	3045		3550		3310	2800
Deformation at failure, in.	.190		.231		.269	.285
Average voids, per cent	8.40		7.19		3.54	2.79

TABLE 11

RESULTS OF STABILITY TESTS ON HOT-MIX ASPHALTIC CONCRETE MIXTURES TEXAS HIGHWAY DEPARTMENT S-317—TYPE "D"

Coarse Aggregate—Washed River Gravel
Fine Aggregate—Limestone Screenings and Field Sand

Mixture Constant
Type of Asphalt—Variable

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT			
	Series LD_3	Series LD	Series LD_1	Series LD_2
Washed river gravel	54.96	54.96	54.96	54.96
Limestone screenings	24.64	24.64	24.64	24.64
Sand "B", field sand	15.16	15.16	15.16	15.16
Asphalt cement	5.25	5.25	5.25	5.25
Grade of asphalt	OA-55	OA-90	OA-135	OA-230

	Results of Stability Tests Marshall Compaction Procedure			
Hveem Stability:				
Stability, per cent	41.9	40.0	35.0	40.1
Angle-internal friction, °	32.1	34.3	30.5	35.0
Cohesion, C, psi.	28	32	14	27
Marshall Stability:				
Stability, lb.	1120	1005	880	850
Flow, in.	.149	.154	.085	.078
Texas Highway Department Punching Shear:				
Stability, lb.	386	320	229	148
Deformation at failure, in.	.106	.085	.091	.066
Direct Compression:				
Elastic limit, lb.	990	630	475	390
Ultimate strength, lb.	1425	870	685	530
Modulus of elasticity, psi.	4990	4580	3520	3030
Cohesiometer:				
Load per in. corrected to 3" height, g.	273	213	163	137
Average voids, per cent	4.24	3.356	2.77	3.20
	Asphalt Institute Compaction Procedure			
Asphalt Institute Stability:				
Stability, lb.	3770	3310	3130	2940
Deformation at failure, in.	.270	.269	.269	.204
Average voids, per cent	5.14	3.54	3.66	3.33

TABLE 12

RESULTS OF STABILITY TESTS ON HOT-MIX ASPHALTIC CONCRETE MIXTURES TEXAS HIGHWAY DEPARTMENT S-317—TYPE "D"

Coarse Aggregate—Washed River Gravel
Fine Aggregate—Siliceous Sands and Limestone Dust

Aggregate Gradation Constant
Asphalt Cement OA-90 Variable

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT			
	Series SD	Series PD	Series QD	Series RD
Washed river gravel	57.60	57.30	56.85	56.40
Sand "A" concrete sand	19.20	19.10	18.95	18.80
Sand "B", field sand	14.40	14.32	14.21	14.10
Limestone dust	4.80	4.78	4.74	4.70
Asphalt cement OA-90	4.00	4.50	5.25	6.00
	Results of Stability Tests Marshall Compaction Procedure			
Hveem Stability:				
Stability value, per cent	34.7	31.8	25.5	0
Angle internal friction, °	32.1	31.0	26.8	13.2
Cohesion, C, psi.	37	23	6	2
Marshall Stability:				
Stability, lb.	760	625	520	570
Flow, in.	.087	.115	.197	.206
Texas Highway Department Punching Shear:				
Stability value	145	164	244	235
Deformation at failure, in.	.087	.110	.122	.154
Direct Compression:				
Elastic limit, lb.	470	400	360	350
Ultimate strength, lb.	590	520	475	530
Modulus of elasticity, psi.	3200	1690	1550	540
Cohesiometer:				
Load per in. corrected to 3" height, g.	116	135	168	116
Average voids, per cent	5.73	4.42	2.64	2.04
	Asphalt Institute Compaction Procedure			
Asphalt Institute Stability:				
Stability, lb.	1735	2360	1780	1380
Deformation at failure, in.	.135	.144	.212	.227
Average voids, per cent	5.68	3.59	2.56	2.10

Results of Tests on Laboratory Cut-Back Asphaltic Concrete Mixtures

The laboratory cut-back asphaltic concrete specimens were all made using the same aggregate combination with varying percentages of cut-back asphalt. Three series were molded by the Marshall method and two series were compacted by the Texas Highway Department method. As previously indicated the results obtained from the specimens compacted by the Asphalt Institute method were too erratic to be of any value and are not reported. The specimens compacted by the Marshall method were not considered to be entirely satisfactory; however, the results of the stability tests on these specimens are shown. The test results obtained by the various stability tests on the five series of cut-back asphaltic concrete mixtures are shown in Table 13. The subscript T designates the two series compacted by the Texas Highway Department procedure. The composition of the mixtures is shown in Table 4.

TABLE 13

RESULTS OF TESTS ON CUT-BACK ASPHALTIC CONCRETE TEXAS HIGHWAY DEPARTMENT S-309—TYPE "M"

Coarse Aggregate—Crushed Limestone
Fine Aggregate—Siliceous Sands
Aggregate Gradation Constant
Asphalt Content Variable—RC-2

Marshall Compaction Procedure—BM_M, DM_M, EM_M

Texas Highway Department Compaction Procedure—BM_T, EM_T

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT				
	Series BM_T	Series BM_M	Series DM_M	Series EM_T	Series EM_M
Crushed limestone, ½″ to no. 10	65.80	65.80	65.45	65.45	66.15
Sand "A", concrete sand	14.10	14.10	14.02	14.02	14.17
Sand "B", field sand	14.10	14.10	14.03	14.03	14.18
RC-2 cut-back asphalt	6.00	6.00	6.50	5.50	5.50
	Results of Stability Tests				
Hveem Stability:					
Stability, per cent	43.2	19	23	50.4	20.4
Angle of internal friction, °	37.2	26.9	25.1	38.6	26.4
Cohesion, psi.	17	35	39	38	34
Marshall Stability:					
Stability, lb.	710	115	185	240	220
Flow, in.	.082	.077	.099	.081	.081
Texas Highway Department Punching Shear:					
Stability, lb.	105	58	37	102	88
Deformation at failure, in.	.114	.111	.085	.081	.103
Direct Compression:					
Elastic limit, lb.	475	225	125	480	300
Ultimate strength, lb.	570	315	150	695	412
Modulus of elasticity, psi.	4380	2615	940	5670	2820
Cohesiometer:					
Load per in. corrected to 3″ height, g.	94	62	57	88	64
Average voids, per cent	7.63	15.06	15.23	8.93	16.06

Results of Tests on Hot-Mix Asphaltic Concrete Mixtures From Texas Highway Department Construction Projects

The results of the Stability tests on the five hot-mix asphaltic concrete mixtures furnished by the Texas Highway Department from their construction projects are shown in Tables 14 and 15. The composition of the mixtures as determined by field extraction tests is shown in Table 5. Table 14 presents the results of the stability tests on the three Type "D" asphaltic concrete mixtures. The mixtures compacted by the Marshall method are designated by the subscript M and the mixtures compacted by the Texas Highway Department method by the subscript T. Table 15 shows the results of the tests on the two Type "C" asphaltic concrete mixtures.

TABLE 14

RESULTS OF TESTS ON MIXTURES OBTAINED FROM TEXAS HIGHWAY DEPARTMENT CONSTRUCTION PROJECTS CONFORMING TO HOT-MIX ASPHALTIC CONCRETE S-317—TYPE "D"

Marshall Compaction Procedures—SB_M, SG_M, SU_M

Texas Highway Department Compaction—SB_T, SG_T, SU_T

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT					
	Series SB_M	Series SB_T	Series SG_M	Series SG_T	Series SU_M	Series SU_T
From Field Extraction:						
Pass ⅝″ ret'd. no. 10	52.0	52.0	54.8	54.8	49.4	49.4
Pass no. 10, ret'd. no. 200	40.0	40.0	36.5	36.5	40.7	40.7
Pass no. 200	3.6	3.6	3.8	3.8	5.3	5.3
Asphalt cement	4.4	4.4	4.9	4.9	4.6	4.6
Grade of asphalt	OA-90	OA-90	OA-230	OA-230	OA-230	OA-230
	Results of Stability Tests					
Hveem Stability:						
Stability, per cent	55.0	56.0	63.7	57.0	63.7	58
Angle internal friction, °	34.5	35.6	38.4	38.8	39.5	37.6
Cohesion, C, psi.	49	47	53	36	55	51
Marshall Stability:						
Stability, lb.	1285	2280	930	1345	1740	2050
Flow, in.	.107	.108	.091	.118	.120	.144
Texas Highway Department Punching Shear:						
Stability, lb.	375	479	142	185	310	349
Deformation at failure, in.	.089	.093	.069	.084	.117	.093
Direct Compression:						
Elastic limit, lb.	1630	1450	540	800	1280	1770
Ultimate strength, lb.	1920	1740	730	1030	1795	2250
Modulus of elasticity, psi.	13150	11960	4530	8830	9960	18500
Cohesiometer:						
Load per in. corrected to 3″ height, g.	213	285	73	101	158	251
Average voids, per cent	5.14	2.16	4.88	2.72	5.19	2.14
	Asphalt Institute Compaction Procedure					
Asphalt Institute Stability:						
Stability, lb.	3490		2390		4350	
Deformation at failure, in.	.378		.252		.343	
Average voids, per cent	9.88		8.06		8.10	

TABLE 15

RESULTS OF TESTS ON MIXTURES OBTAINED FROM THE TEXAS HIGHWAY DEPARTMENT CONSTRUCTION PROJECTS CONFORMING TO HOT-MIX ASPHALTIC CONCRETE S-317—TYPE "C"

Marshall Compaction Procedures—SC_M, SP_M

Texas Highway Department Compaction—SC_T SP_T

	COMPOSITION OF MIXTURES, PER CENT BY WEIGHT			
	Series SP_M	Series SP_T	Series SC_M	Series SC_T
From Field Extraction:				
Pass 1" screen, ret'd. no. 10	55.9	55.9	59.5	59.5
Pass no. 10, ret'd. no. 200	35.5	35.5	29.3	29.3
Pass no. 200	4.6	4.6	5.1	5.1
Asphalt cement	4.0	4.0	6.1	6.1
Grade asphalt cement	OA-90	OA-90	OA-135	OA-135
	Results of Stability Tests			
Hveem Stability:				
Stability, per cent	54.8	57.2	52.8	49.8
Angle of internal friction, °	35.5	38.0	34.0	31.4
Cohesion, C, psi.	49	39	55	65
Marshall Stability:				
Stability, lb.	1240	1460	2200	2115
Flow, in.	.099	.082	.158	.168
Texas Highway Department Punching Shear:				
Stability, lb.	370	239	410	574
Deformation at failure, in.	.075	.078	.096	.099
Direct Compression:				
Elastic limit, lb.	1370	900	1400	2070
Ultimate strength, lb.	1590	1120	1930	2660
Modulus of elasticity, psi.	14,500	8570	8000	15,250
Cohesiometer:				
Load per in. corrected to 3" height, g.	119	150	269	332
Average voids, per cent	4.83	2.97	2.72	1.08
	Asphalt Institute Compaction Procedure			
Asphalt Institute Stability:				
Stability, lb.	2060		3700	
Deformation at failure, in.	.228		.430	
Average voids, per cent	7.56		6.32	

CORRELATIONS BETWEEN THE STABILITY TESTS

The primary objective of this research project was to determine whether or not any correlation exists between the six stability tests studied. It seems reasonable to expect that if correlation is found to exist between the stability test results for all of the mixtures tested in this project then it probably exists for similar mixtures not actually tested. In order to study the correlation between the various stability values they were plotted against each other. The results of plotting the values in this manner are shown in Figures 14 to 34 which follow. These figures show clearly and simply the relationship between the various stability values.

The relationships for the elastic limit in direct compression are not plotted because the ultimate strength and elastic limit values practically parallel each other and the plotting of the elastic limit values would not indicate any information not shown by the plotting of the ultimate strength. The cohesion as determined from the Hveem stability test was not plotted because of the lack of consistency in the values. None of the deformation values were plotted for correlation purposes, but they are shown in Figures 35, 36, and 37 for the laboratory hot-mix asphaltic concrete series.

Figure 14 shows the relationship between the Hveem stability and the angle of internal friction obtained from the Hveem stability test data. Since the Hveem stability value is generally considered to depend primarily upon the angle of internal friction it was expected that good correlation would exist. Figure 14 confirms this since it shows good correlation between the Hveem stability value and the angle of internal friction. Figure 15 shows the relationship between the Hveem stability and the cohesion determined from the cohesiometer test. Figure 15 indicates complete lack of correlation between the Hveem stability and the cohesion as determined by the cohesiometer test.

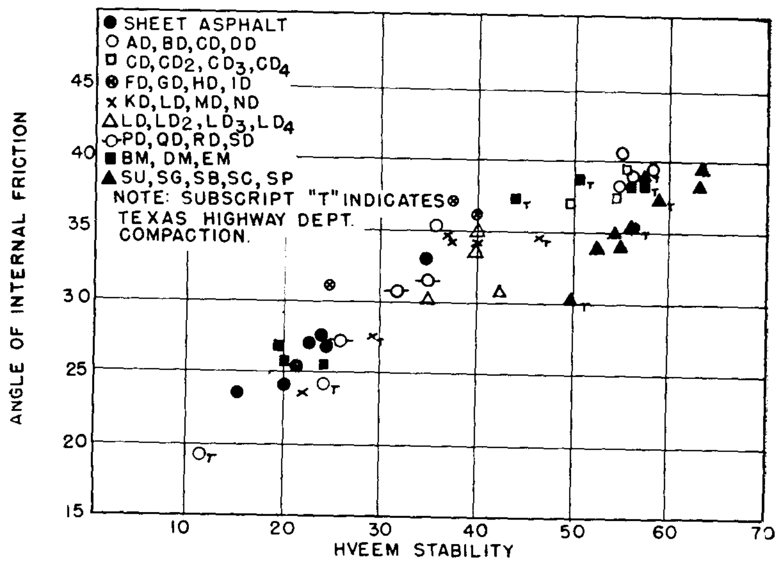


Figure 14. Relationship between Hveem stability and angle of internal friction.

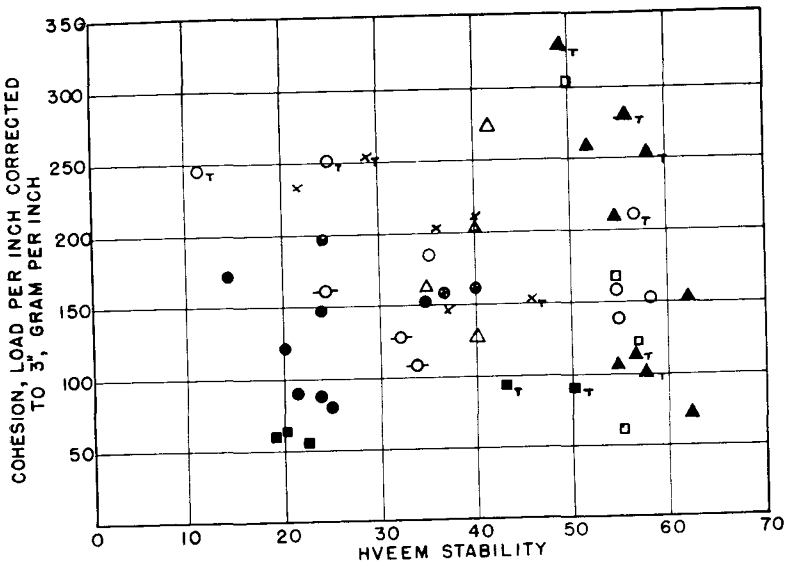


Figure 15. Relationship between Hveem stability and cohesion from cohesiometer test.

Figures 16 to 20 show the relationship between the Hveem stability values, the angle of internal friction from the Hveem stability test data and the Marshall stability, the Texas Highway Department punching shear stability, the ultimate strength in direct compression, the modulus of elasticity in direct compression, and the Asphalt Institute stability respectively.

Examination of Figures 16 to 20 indicates that no consistent relationship exists between the Hveem stability or the angle of internal friction and any of the other stability values with the possible exception of the modulus of elasticity in direct compression. It will be noted that the lack of any consistent relationship applies equally well to individual series and to groups of series.

Figure 19 shows the relationship between Hveem stability, angle of internal friction, and modulus of elasticity. The modulus of elasticity values were found to be quite variable between individual tests on specimens from the same mixture. It was very difficult to repeat results for modulus of elasticity. For these reasons it is questionable whether or not the very approximate correlation indicated by Figure 19 can be considered to have any meaning.

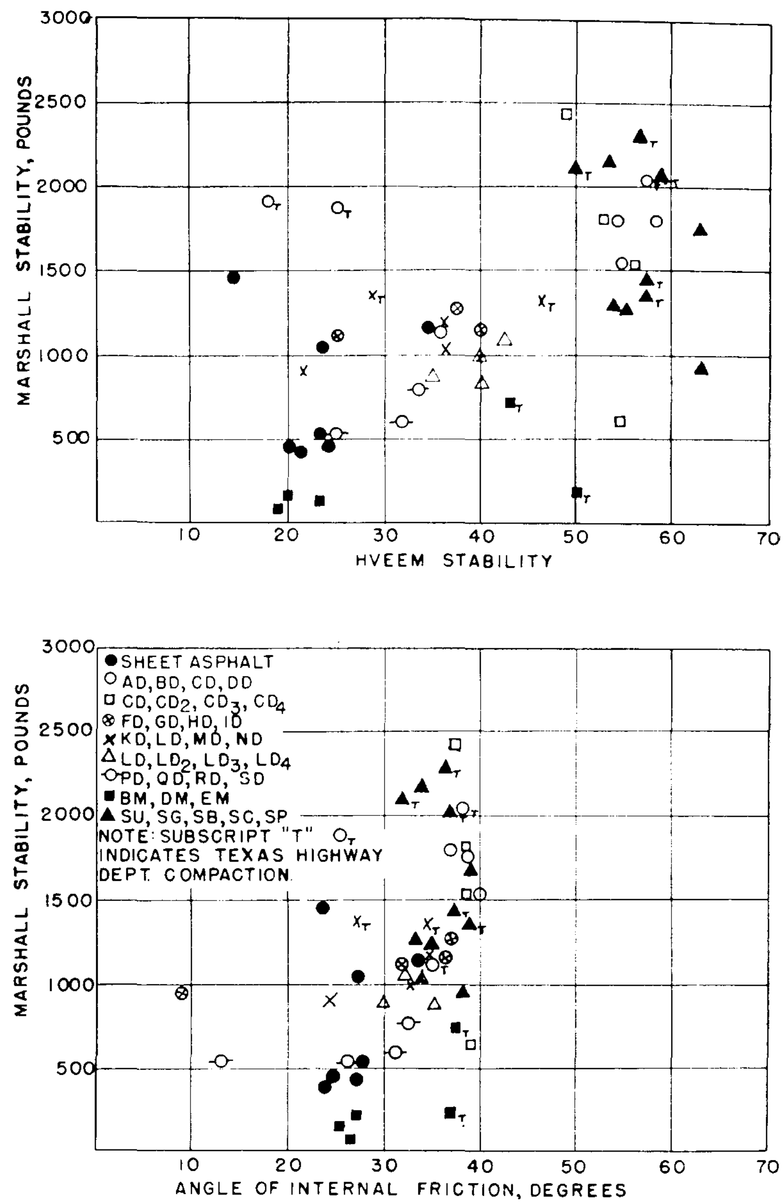


Figure 16. Relationship between Hveem stability, angle of internal friction and Marshall stability.

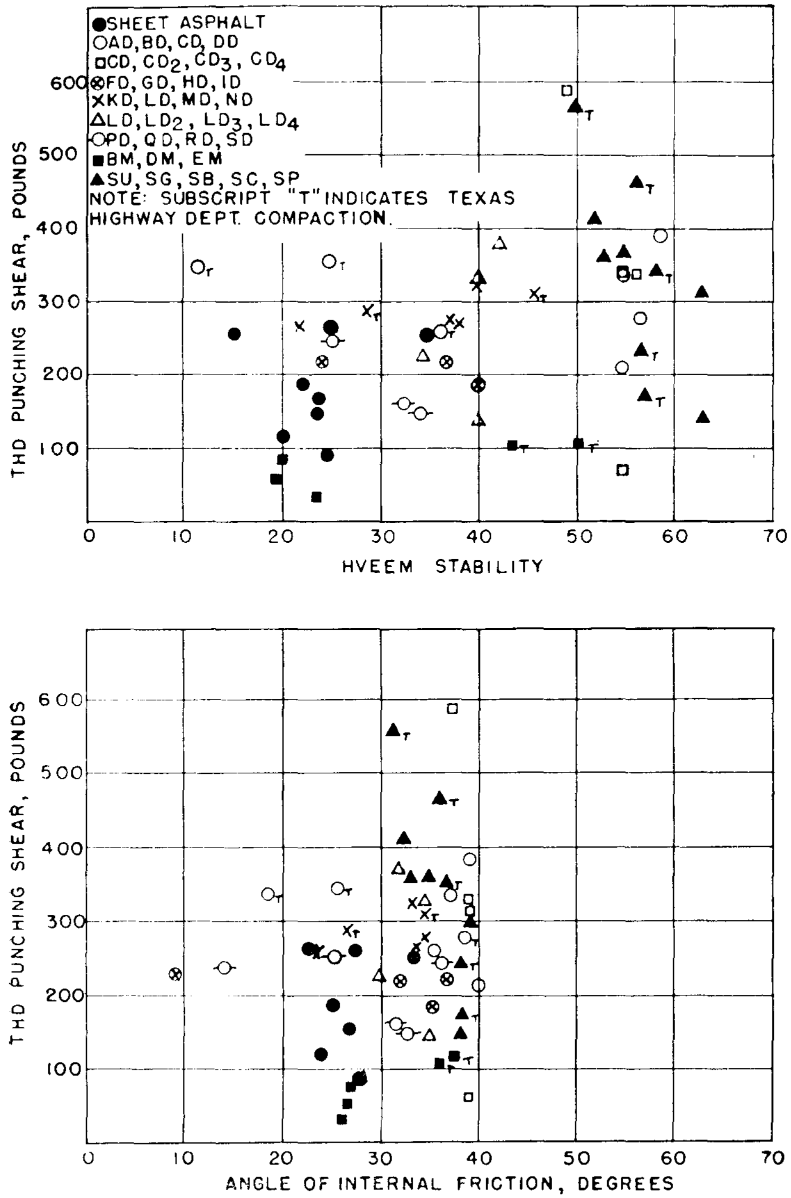


Figure 17. Relationship between Hveem stability, angle of internal friction and Texas Highway Department punching shear stability.

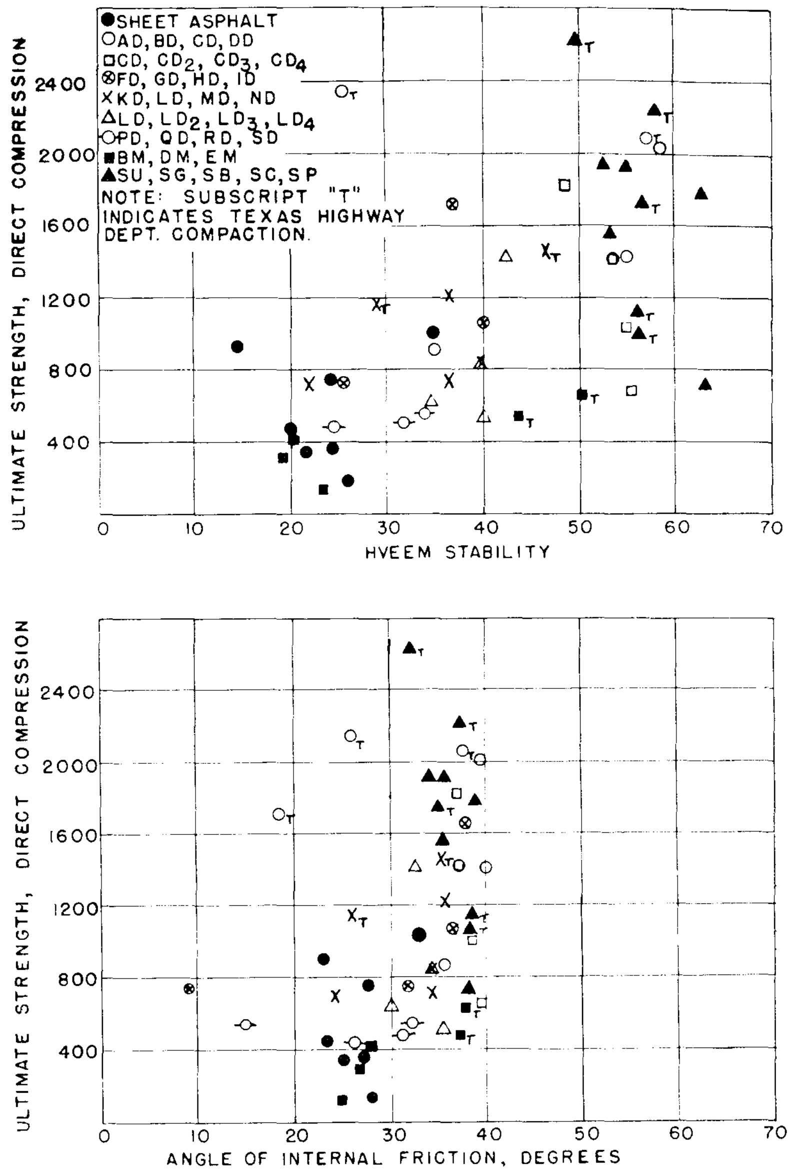


Figure 18. Relationship between Hveem stability, angle of internal friction, and ultimate strength in direct compression.

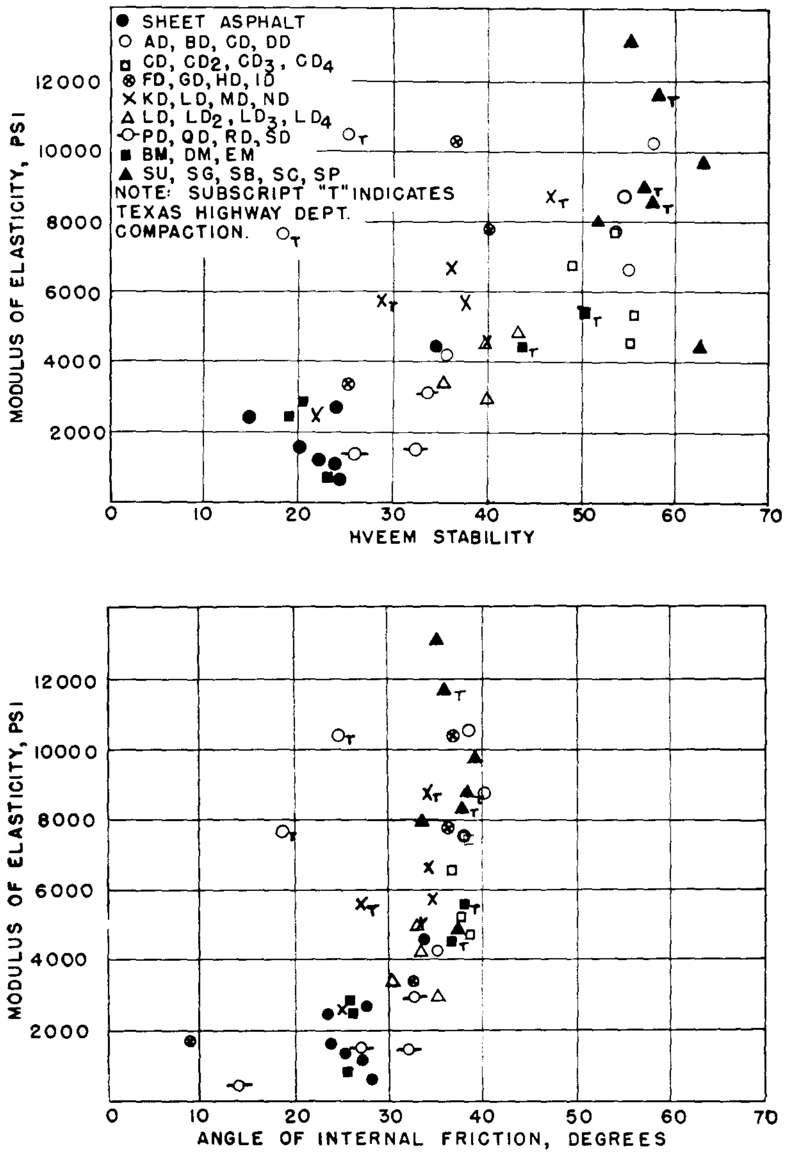


Figure 19. Relationship between Hveem stability, angle of internal friction and modulus of elasticity in direct compression.

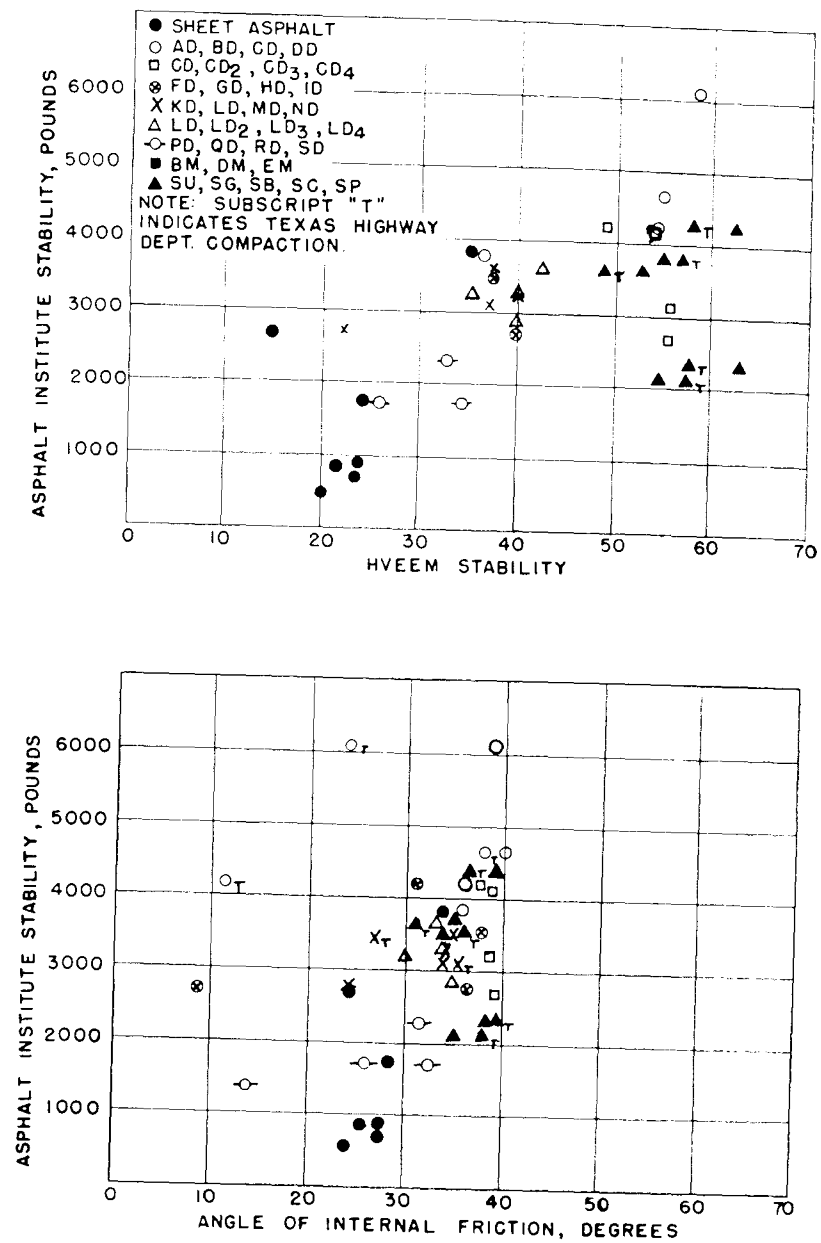


Figure 20. Relationship between Hveem stability, angle of internal friction and Asphalt Institute stability.

Figures 21 to 25 show the relationship between the cohesion as determined by the cohesiometer test and the Marshall stability, the Texas Highway Department punching shear stability, the ultimate strength in direct compression, the modulus of elasticity in direct compression, and the Asphalt Institute stability respectively.

Figure 21 indicates fair correlation between the Marshall stability and the cohesion. While the relationship is far from perfect it does indicate that the Marshall stability is closely allied to the cohesion as measured by the cohesiometer test.

Figure 22 shows rather good correlation between the Texas Highway Department punching shear values and the cohesion. The correlation in this case seems to be good enough to warrant the conclusion that these two tests measure essentially the same characteristics of the material.

Figures 23 and 25 indicate a rather general but not very precise relationship between the ultimate strength in direct compression and the cohesion and between the Asphalt Institute stability and the cohesion. The only conclusion which seems justified in either case is that the values trend in the same direction; that is, the ultimate strength in direct com-

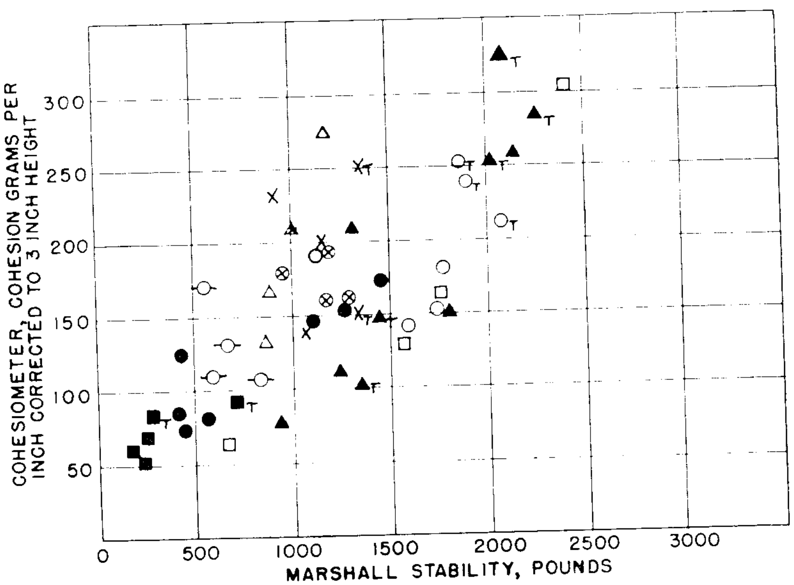


Figure 21. Relationship between cohesion and Marshall stability.

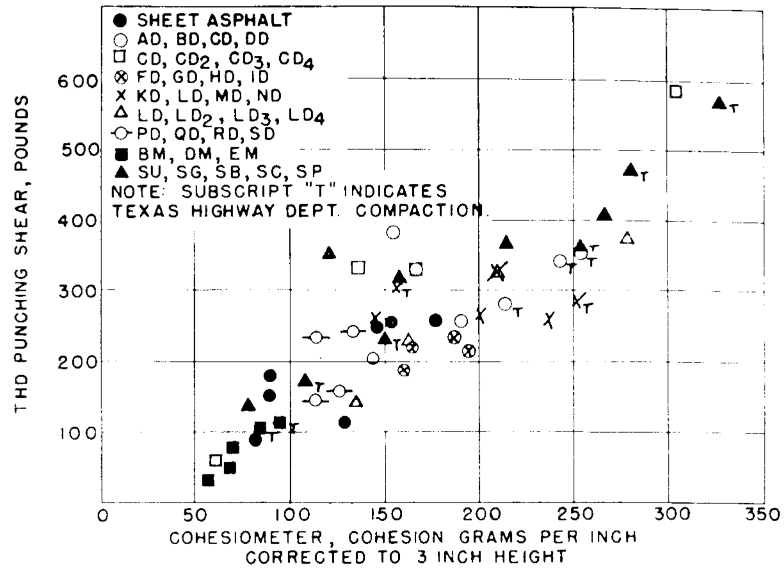


Figure 22. Relationship between cohesion and Texas Highway Department punching shear stability.

pression and the Asphalt Institute stability values generally increase with an increase in cohesion. Groups of series do not follow this pattern in all cases.

Figure 24 shows that there is no correlation between cohesion as measured by the cohesiometer and the modulus of elasticity determined from the direct compression test.

Figures 26 to 28 show the relationship which exists between the Marshall stability and the Texas Highway Department punching shear, the ultimate strength in direct compression, the modulus of elasticity in direct compression, and the Asphalt Institute stability.

The correlation between the Marshall stability and the Texas Highway Department punching shear is rather good as shown in Figure 26. Since both of these stability values showed good correlation with cohesion it seems logical that there should be good correlation between them.

Figure 27 also indicates a rather consistent relationship between the Marshall stability and the ultimate strength in direct compression. The correlation is good enough to indicate that these stability values measure essentially the same characteristics of the materials.

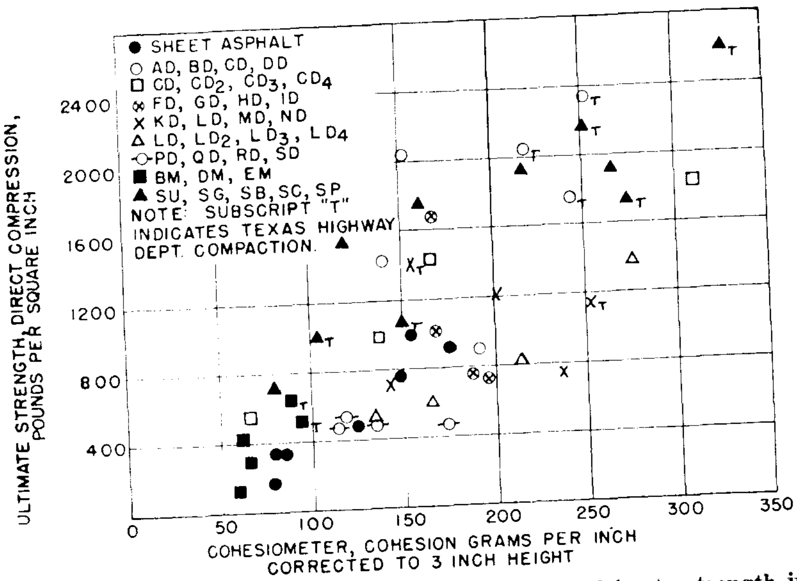


Figure 23. Relationship between cohesion and ultimate strength in direct compression.

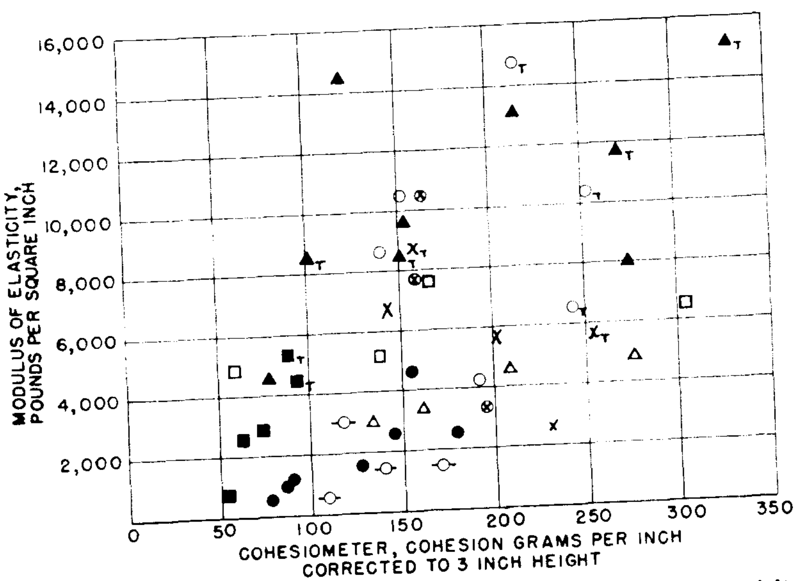


Figure 24. Relationship between cohesion and modulus of elasticity in direct compression.

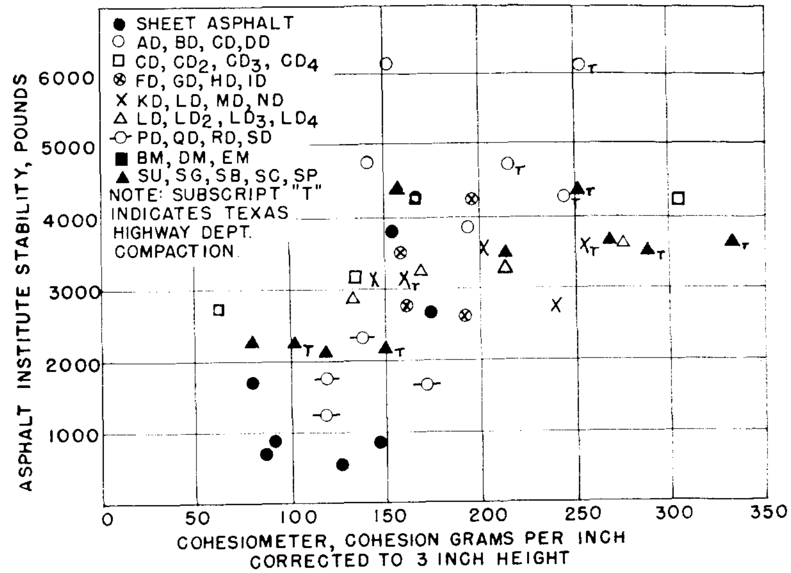


Figure 25. Relationship between cohesion and Asphalt Institute stability.

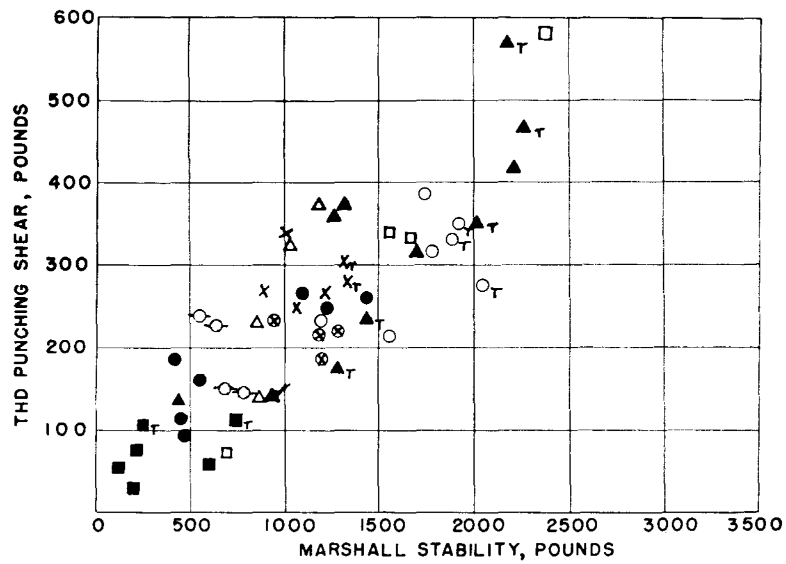


Figure 26. Relationship between Marshall stability and Texas Highway Department punching shear.

Figure 28 indicates no consistent relationship between the Marshall stability and the modulus of elasticity in direct compression.

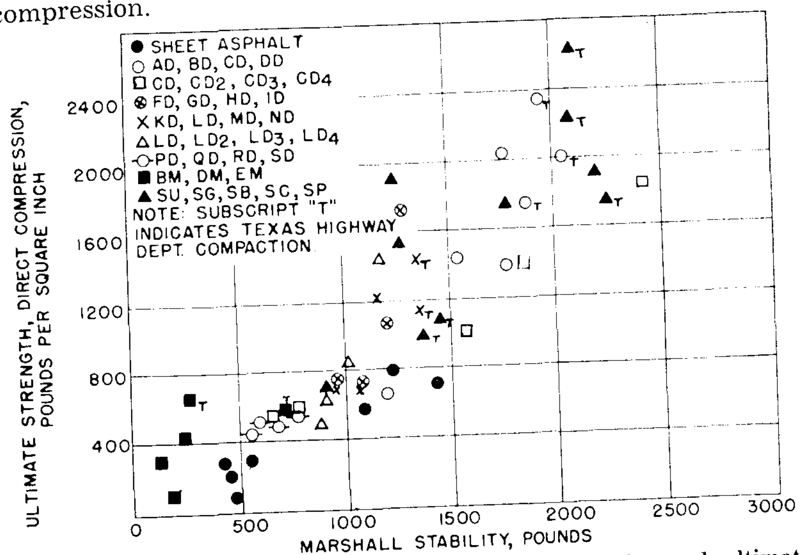


Figure 27. Relationship between Marshall stability and ultimate strength in direct compression.

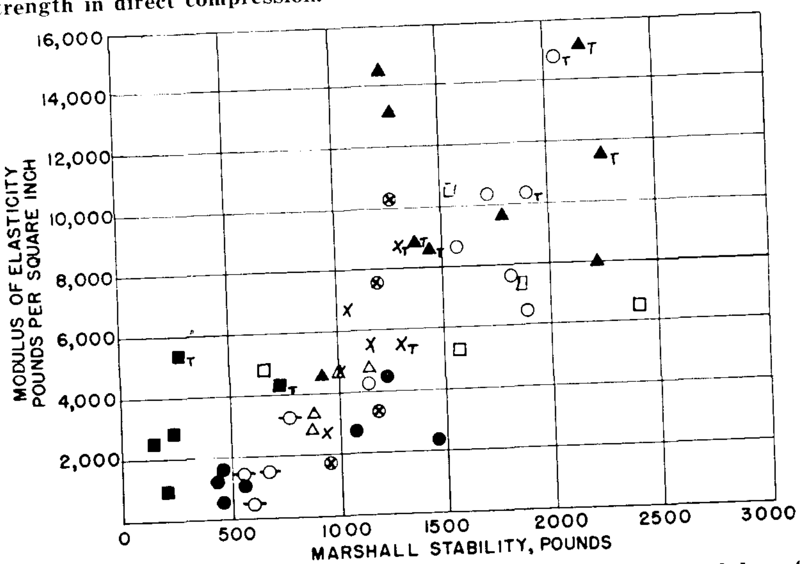


Figure 28. Relationship between Marshall stability and modulus of elasticity in direct compression.

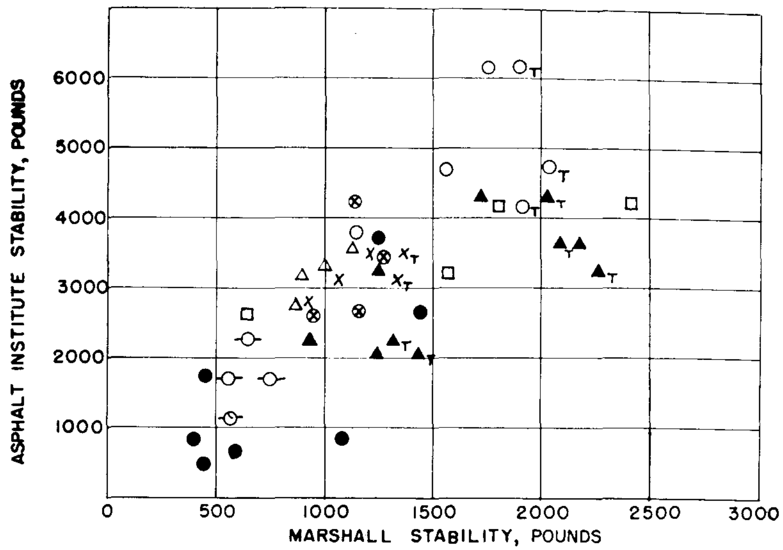


Figure 29. Relationship between Marshall stability and Asphalt Institute stability.

Figure 29 indicates a general relationship between the Marshall stability and the Asphalt Institute stability. The relationship is not consistent enough to warrant a conclusion that the two values show good correlation.

Figures 30 to 34 show the relationship between the Asphalt Institute stability, the Texas Highway Department punching shear stability, the ultimate strength in direct compression, and the modulus of elasticity in direct compression.

Figure 30 shows fair correlation between the Texas Highway Department punching shear and the ultimate strength in direct compression.

Figures 31 and 34 indicate that no consistent relationship exists between either the Texas Highway Department punching shear or the Asphalt Institute stability and the modulus of elasticity in direct compression.

Figure 32 shows little, if any, correlation between the Texas Highway Department punching shear stability and the Asphalt Institute stability.

Figure 33 shows some correlation between the ultimate strength in direct compression and the Asphalt Institute stability. The relationship is considered good enough to indicate that the two stability values probably measure the characteristics of the mixtures in about the same manner.

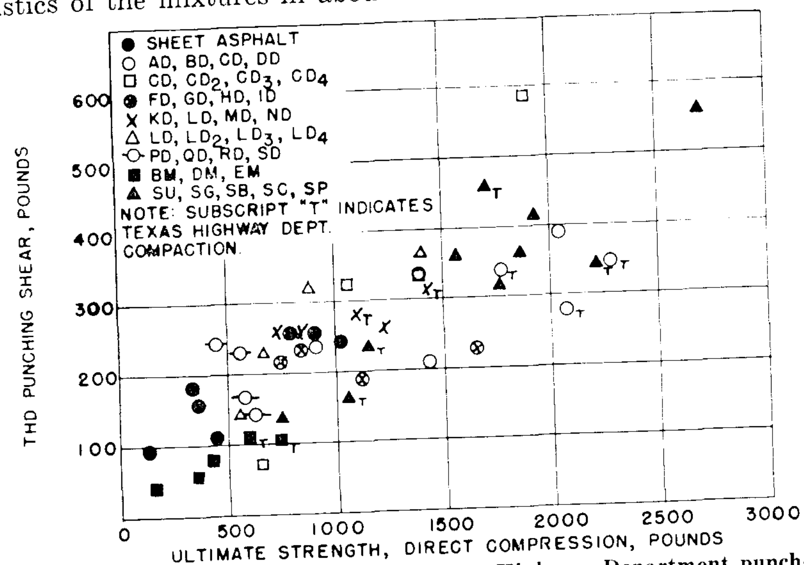


Figure 30. Relationship between Texas Highway Department punching shear and the ultimate strength in direct compression.

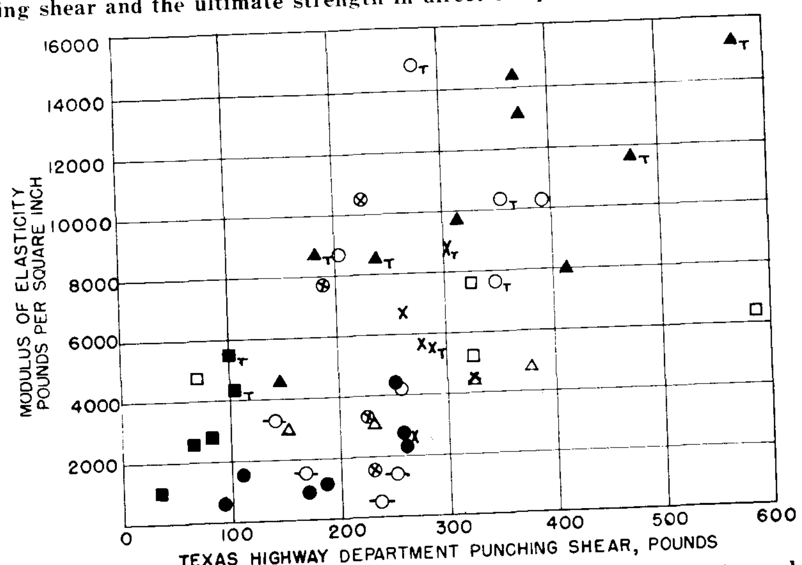


Figure 31. Relationship between Texas Highway Department punching shear and the modulus of elasticity in direct compression.

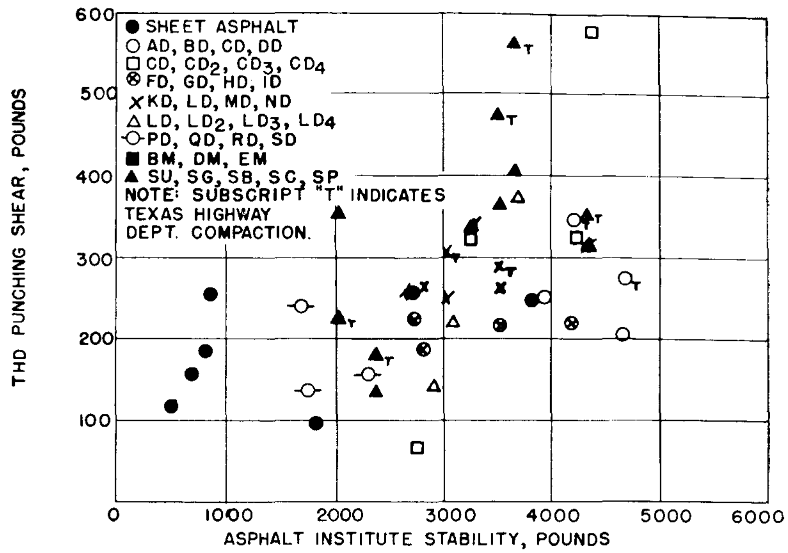


Figure 32. Relationship between Texas Highway Department punchin shear stability and the Asphalt Institute stability.

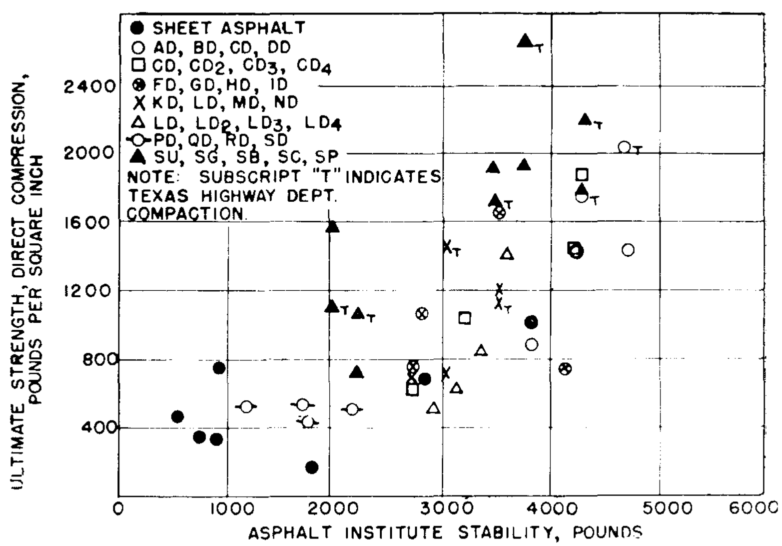


Figure 33. Relationship between Asphalt Institute stability and ultimate strength in direct compression.

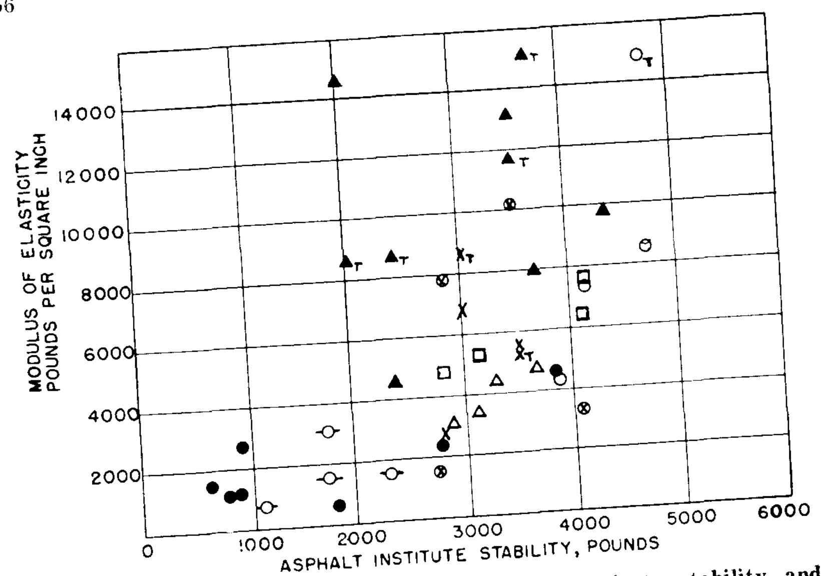


Figure 34. Relationship between Asphalt Institute stability and modulus of elasticity in direct compression.

EFFECT OF VARIATIONS IN CONSTITUENTS UPON THE STABILITY OF HOT-MIX ASPHALTIC CONCRETE AS MEASURED BY THE VARIOUS STABILITY TEST PROCEDURES

The results of the stability determinations on the 27 laboratory hot-mix asphaltic concrete series are plotted in Figures 35, 36, and 37. All of the values determined including the deformation values are shown in these figures. Figures 35, 36, and 37 show the relationship between the stability values, the asphalt content of the mixtures, the consistency of the asphalt used in the mixtures, and the type of aggregate used in the mixtures. The curves indicate a number of facts concerning variations in the stability values with variation in the components of the mixtures.

The Hveem stability and the angle of internal friction obtained from the Hveem stability test remain practically constant for a given aggregate combination as the asphalt content varies until the asphalt content is large enough to reduce the voids in the mixture to the point where the asphalt becomes a lubricant. This is well illustrated by the results for the three mixtures AD_T, BD_T, and CD_T compacted by the Texas Highway Department procedure. Figures 35, 36, and 37

indicate that this lubrication with its corresponding drop in Hveem stability and angle of internal friction occurs when the voids, measured by the procedure used, at normal air temperature, are reduced to about two per cent. The Hveem stability and angle of internal friction values go down rapidly for mixtures showing about two per cent voids or less.

Figures 35 and 36 show that the Hveem stability and the angle of internal friction are independent of the hardness of the asphalt cement used in the mixtures. The curves for both the CD series and the LD series show that both the Hveem stability and the angle of internal friction remain practically constant as the type of asphalt cement is varied from OA-55 to OA-230.

The effect of variations in the characteristics of the aggregates on the Hveem stability and the angle of internal friction is also illustrated by Figures 35, 36, and 37. For maximum values, values at 5.25 per cent asphalt content, and values interpolated at four per cent voids the curves show the following values for the Hveem stability and the angle of internal friction for those specimens compacted by the Marshall procedure with OA-90 asphalt cement.

	HVEEM STABILITY			ANGLE OF INTERNAL FRICTION		
	Per Cent			Degrees		
	Maximum	At 5.25% Asphalt	At 4% Voids	Maximum	At 5.25% Asphalt	At 4% Voids
Crushed limestone coarse aggregate, limestone screenings and field sand	58.4	58.4	49	40.4	38.9	37
Crushed limestone coarse aggregate, siliceous sand, field sand and limestone dust	40.0	37.0	37.5	37.5	37.5	37
Gravel coarse aggregate, limestone screenings and field sand	40.0	40.0	40	34.8	34.3	34
Gravel coarse aggregate, siliceous sand, field sand and limestone dust	35.4	25.5	29	32.1	26.8	30

The validity of interpolating on the curves for the values shown at four per cent voids is questionable particularly for those cases in which there is considerable variation between the two values interpolated between.

The results show that both the Hveem stability and the angle of internal friction determined from the Hveem data

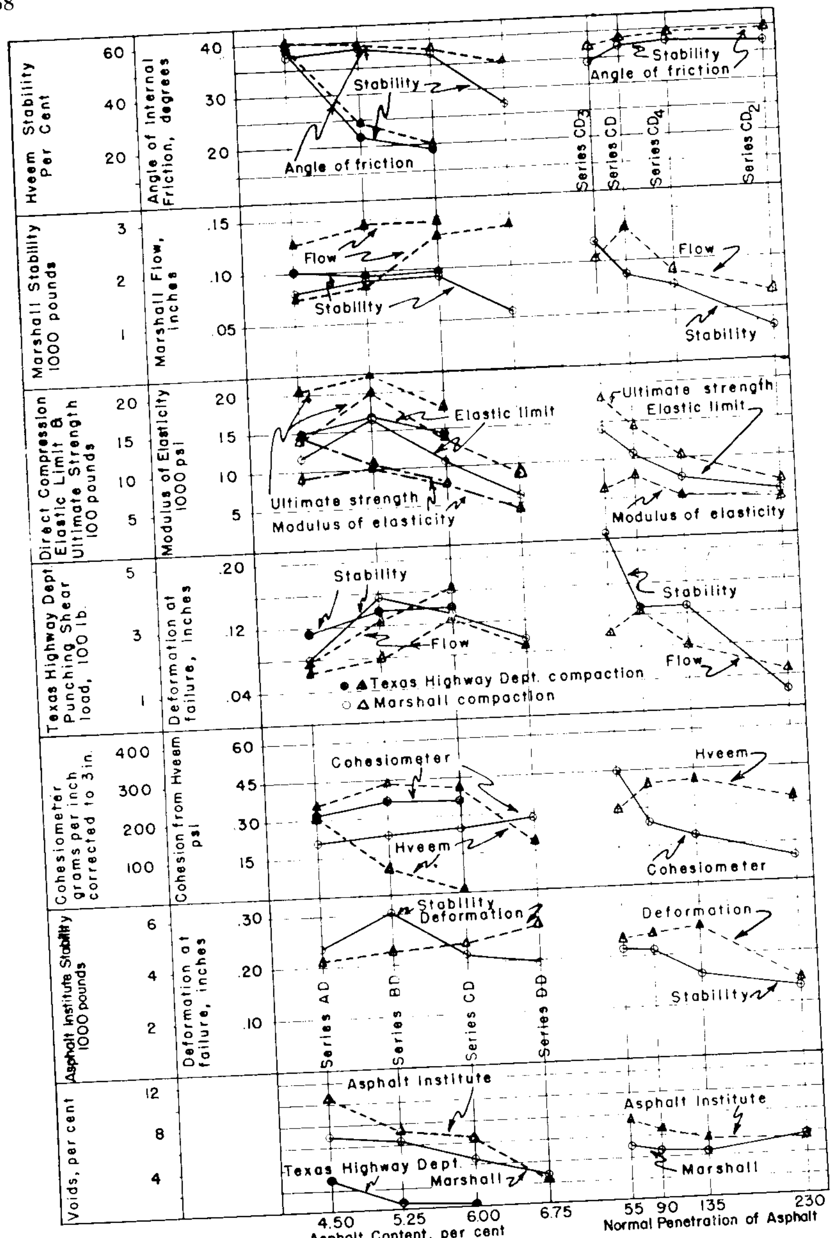


Figure 35. Results of stability tests on hot mix asphaltic concrete. Series AD, BD, CD, DD (Crushed limestone coarse aggregate and varying asphalt penetration).

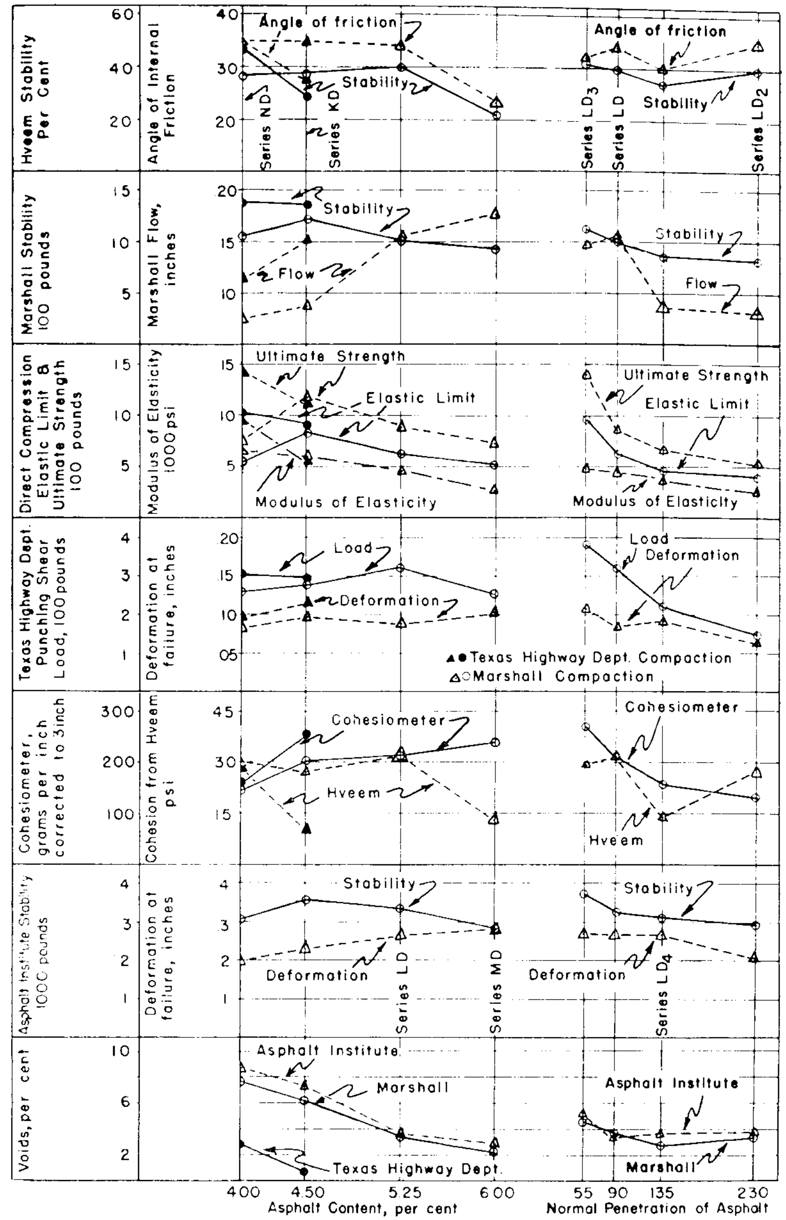


Figure 36. Results of stability tests on hot-mix asphaltic concrete, Series KD, LD, MD, ND (Gravel coarse aggregate and varying asphalt penetration).

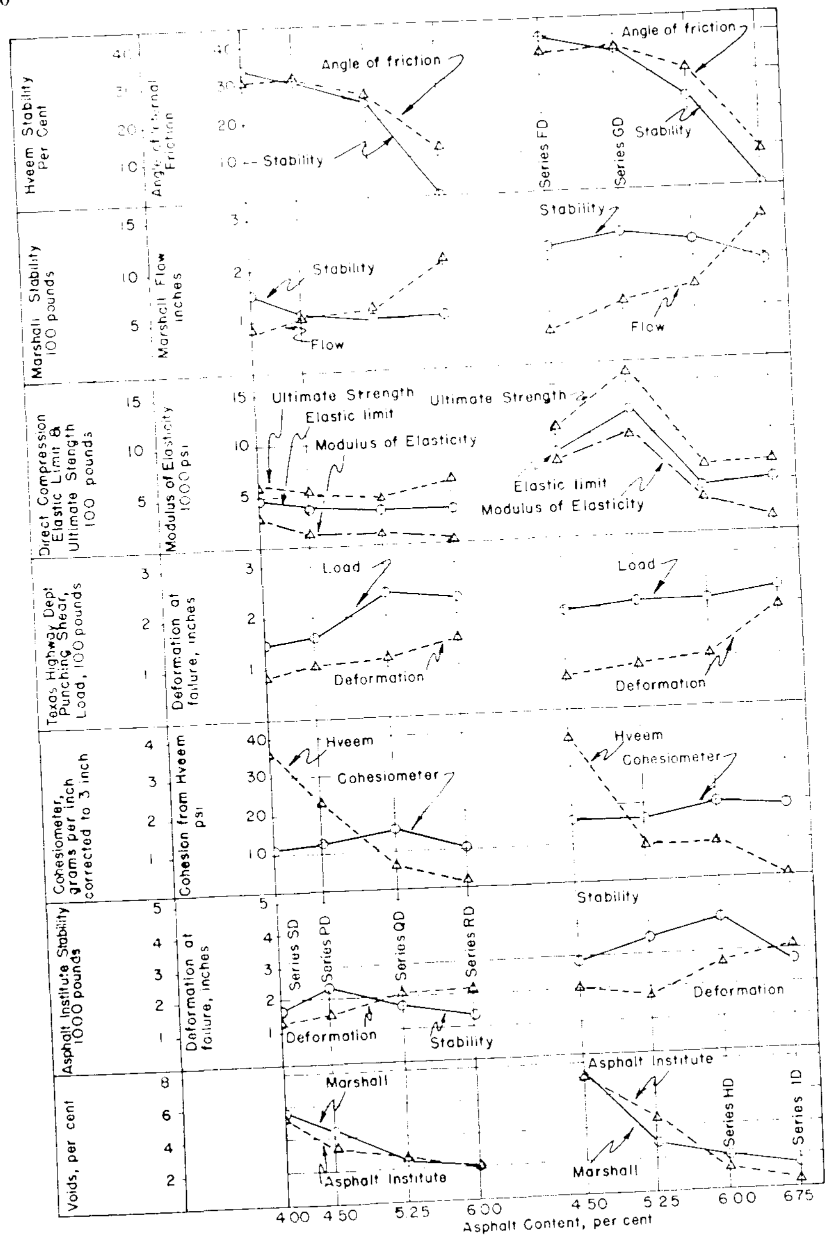


Figure 37. Results of stability tests on hot-mix asphaltic concrete, series PD, QD, RD, SD (Gravel coarse aggregate) and FD, GD, HD, ID (Crushed limestone coarse aggregate).

are sensitive to differences in the aggregates for mixtures with voids in excess of about two per cent. The angle of internal friction does not show as large a percentage variation for the mixtures studied as does the stability. Furthermore the differences are not indicated in exactly the same way by the two test constants. The Hveem stability value evidently depends partially upon some factor other than the angle of internal friction as determined in this investigation.

The Marshall stability, ultimate strength and elastic limit in direct compression, the Texas Highway Department punching shear, and the Asphalt Institute stability values all show the same general variation of stability value with respect to changes in asphalt content with a given aggregate. Figures 35, 36, and 37 show that the stability values for all of the above test procedures rise to a maximum value and then fall off as the asphalt content increases. Furthermore, all of these stability values are sensitive to variations in the hardness of the asphalt cement. As the asphalt cement becomes harder the stability increases. The results do not indicate that this variation with hardness of asphalt cement is entirely independent of the aggregate.

Variations in aggregate combinations are indicated by differences in the stability values for the Marshall Stability, the ultimate strength in direct compression, the Asphalt Institute stability, and the Texas Highway Department punching shear stability as follows: the values shown are the maximum values for the mixtures compacted by the Marshall procedure with OA-90 asphalt cement.

	Marshall Stability, Pounds	Ultimate Strength, Pounds	Asphalt Institute Stability, Pounds	Texas Highway Department Punching Shear, Pounds
Crushed limestone coarse aggregate, limestone screenings and field sand	1760	2025	6070	395
Crushed limestone coarse aggregate, siliceous sand, field sand and limestone dust	1260	1670	4130	229
Gravel coarse aggregate, limestone screenings and field sand	1200	1205	3550	320
Gravel coarse aggregate, siliceous sand, field sand, and limestone dust	760	590	2360	244

The Marshall stability, ultimate strength, and Asphalt Institute stability show the same general relationship for the stability of the four different aggregate combinations. This indicates that, for the mixtures tested, the variation in the characteristics of the aggregates is indicated in the same general way by these three stability tests. The Texas Highway Department punching shear values are influenced in a different manner by the variations in the aggregates. The punching shear values seem to be primarily dependent upon the characteristics of the fine aggregate.

The cohesion values as measured by the cohesiometer are shown by Figures 35, 36, and 37 to be primarily dependent upon the asphalt content. In the case of all the series except the PD, QD, RD, SD, series the cohesion increased with an increase in asphalt content. The single exception, the drop in cohesion for series RD, is considered to be due to the fact that this mixture was very rich in asphalt (low voids). It is probable that if higher asphalt contents were used for the other mixtures the same drop in cohesion would be had for these mixtures. The RD series mixture was so rich in asphalt that it was difficult to mold.

Variations in type of aggregate are not reflected by any consistent variation in the cohesion values from the cohesiometer test. Variations in the hardness of the asphalt cement used are indicated by rather pronounced changes in cohesion values. Comparison of the results for the CD series and LD series, Figures 35 and 36, show, however, that the variation in cohesion with changes in hardness of the asphalt is not entirely independent of the aggregate.

The maximum stability as measured by the different stability tests occurs at different asphalt contents for the various tests. No consistent manner of variation is indicated by the test results.

Figures 35, 36, and 37 show the variations in the deformation measured for the various stability tests. The deformation values generally increase with an increase in asphalt content thus indicating the increase in the plasticity of the mixtures. Examination of these deformation values, the flow for the Marshall stability test, and the deformation at maximum load for the Texas Highway Department punching shear and for the Asphalt Institute stability test reveals nothing of value except a very general correlation between the deformation values and cohesion as measured by the cohesiometer.

Figures 35, 36, and 37 also show the cohesion values obtained from the Hveem stability test. These values do not show any consistent variation and do not show any consistent relationship to the cohesion values as determined with the

cohesiometer. The values of the cohesion obtained by reducing the Hveem stability test data were quite erratic for all of the mixtures tested; they showed large variations between individual specimens of the same mixture. On the basis of the poor results obtained the cohesion value determined from the Hveem stability data is considered to be of very little value.

EFFECT OF MOLDING PROCEDURE ON DENSITY OF LABORATORY SPECIMENS

Figures 35, 36, and 37 show the variations in percentage of voids obtained by compacting specimens of hot-mix asphaltic concrete by the Marshall compaction procedure, the Asphalt Institute compaction procedure and the Texas Highway Department compaction procedure. Additional information is also shown in Table 13 for the cut-back asphaltic concrete mixtures and in Tables 14 and 15 for the hot-mix asphaltic concrete mixtures which were obtained from the Texas Highway Department and reheated and compacted by the three procedures.

The Asphalt Institute compaction procedure produced the highest percentage of voids for most of the mixtures with the Marshall compaction procedure being second and the Texas Highway Department compaction procedure showing the smallest voids. There were some cases, however, for which the voids by the Asphalt Institute compaction procedure were less than those for the Marshall procedure.

The differences between the voids obtained by the Asphalt Institute and Marshall compaction procedures seem to be closely connected with the internal friction of the aggregates and the possible lubrication of the mixtures by the asphalt cement. The greatest differences occur for the mixtures with high internal friction for example, AD, BD, CD, SP, SC, SB, SG, and SU. For these mixtures the voids obtained for the Asphalt Institute procedure average about three per cent greater than those for the Marshall compaction procedure. When the asphalt content is high and is producing lubrication in the mixtures, as for mixtures DD, RD, and ID, the differences in voids for the two methods of compaction are small and either procedure may produce the smallest voids. Note also that for the CD and LD series which were molded with OA-230 that the differences in the voids are small and neither procedure produced minimum voids in both cases. For the mixtures with the lowest internal friction, series SD, PD, QD, and RD, the Marshall compaction procedure gave the highest voids for all except series RD. The differences for these series, however, are quite small averaging only slightly more than 0.2 per cent.

The Texas Highway Department compaction procedure gave smaller voids than the other procedures in all cases. For the AD, BD, CD, SP, SC, SB, SG, and SU series the Texas Highway Department compaction procedure produced voids averaging 3.1 per cent less than those obtained by the Marshall compaction procedure and 6.1 per cent less than those for the Asphalt Institute compaction procedure.

The densities obtained by the Texas Highway Department field forces on mixtures SP, SC, SB, SG, and SU were in all cases higher than those obtained for these mixtures in this research project. The voids obtained by the field forces were 3.9, 2.8, 5.2, 6.0, and 5.2 respectively. Examination of Tables 14 and 15 indicates good agreement between these values and those obtained for the Marshall compaction procedure. No explanation can be given for this discrepancy in the results obtained. In view of the variation no firm conclusions as to the relative density obtained by the Texas Highway Department procedure as compared to the other procedures is warranted. This problem must be the subject of additional study.

The considerable differences in density obtained for the three compaction procedures and the considerable differences in stability values for the same mixtures compacted by the Marshall and Texas Highway Department procedures discussed in the following section indicate that the manner of compaction is very important. The results of the limited tests in this project using three compaction procedures show that agreement on a compaction procedure will have to precede any general agreement on the proper stability test. In addition to the compaction procedures investigated here, the kneading compaction procedure used in California[5] and the double plunger procedure recommended by the American Society of Testing Materials (D 1074-49T)[1] are widely used.

EFFECT OF COMPACTION BY THE MARSHALL AND TEXAS HIGHWAY DEPARTMENT METHODS ON THE STABILITY VALUES

Tables 7, 10, 13, 14, and 15 along with Figures 35 and 36 show the relations which exist between the stability values for the specimens of the various mixtures compacted by the Marshall and Texas Highway Department procedures.

Values of the Hveem stability and angle of internal friction show no consistent variation with respect to the two compaction procedures. Where the voids in the mixtures compacted by the Texas Highway Department compaction procedure were enough lower to produce lubrication of the mixture by the asphalt the stability and internal friction are lower for the Texas Highway Department procedure. This last fact is demonstrated by comparison of CD with CD_T and KD with KD_T.

In every case the cohesion as measured by the cohesiometer is higher for the Texas Highway Department compaction procedure than for the Marshall procedure. The percentage difference varies from eight per cent for ND and ND_T to 66 per cent for BD and BD_T with an average value of 39 per cent. This increase in cohesion is probably due to the greater density of the mixtures compacted by the Texas Highway Department procedure.

For the Marshall stability test the values obtained for the mixtures compacted by the Texas Highway Department procedure are higher in all cases except for one mixture, SC. For this mixture the difference in stability values is small for the two methods of compaction being only slightly more than four per cent.

For the Texas Highway Department punching shear stability the values obtained for the mixtures compacted by the Texas Highway Department procedure are higher in all cases except for one mixture, SP.

For the direct compression test there is not as much consistency in the relationship between the type of compaction and the maximum values. Generally the elastic limit and ultimate strength are higher for the mixtures compacted by the Texas Highway Department procedure. Mixtures KD_T (ultimate strength only) SB_T and SP_T show lower values for the Texas Highway Department procedure. The modulus of elasticity values show no consistent relationship. In seven cases the modulus of elasticity values are higher for the Texas Highway Department compaction procedure, in three cases they are higher for the Marshall compaction procedure, and in three cases they are very nearly the same for both compaction procedures. This failure to develop consistent relationships between the two compaction procedures for the direct compression test was probably due to the fact that individual samples showed more variation for the direct compression test than for any of the other test procedures. This was particularly true of the modulus of elasticity values.

The higher values obtained for the Marshall stability, Texas Highway Department punching shear stability and for the elastic limit and ultimate strength in direct compression can probably be accounted for by the higher cohesion obtained for the Texas Highway Department compaction procedure.

GENERAL

One of the difficulties encountered in developing the data for this research project was the lack of agreement between individual test specimens for the same mixture. Extreme care was necessary in maintaining uniformity in the procedures for preparing the specimens in order to obtain reasonable agreement. Even when such care was exercised the test values were sometimes erratic and it was necessary to repeat the tests. The poorest test from the standpoint of reliability of individual values was the direct compression test. The poorest physical property recorded from the standpoint of agreement between individual specimens of the same mixture was the modulus of elasticity. Generally specimens compacted by the Texas Highway Department procedure gave more uniform results than those compacted by the Marshall procedure. The differences were not great, however.

The use of paraffin for coating the samples to prevent the entrance of water during the specific gravity determination was a source of difficulty. On specimens which had some surface roughness the paraffin penetrated the open voids and was very difficult to remove completely. If the paraffin was not all removed it would melt when the specimens were raised to 140°F. and permeate the specimen thus very materially reducing the stability values.

Some of the points covered by this research require additional study. The relation of the density or percentage of voids for the Marshall and Texas Highway Department compaction procedures needs additional study. Adapting the Marshall compaction procedure and the Asphalt Institute compaction procedures to compaction of cut-back asphaltic concrete mixtures and other cold mixtures is worthy of consideration.

This research project has been confined to a study of the relations which exist between the results obtained by a number of laboratory test procedures for determining the stability of asphaltic concrete. The problem of the relationship between the laboratory stability values and the field performance of the mixtures has not been considered.

CONCLUSIONS

1. The Hveem stability values and the angle of internal friction obtained from the Hveem data show good correlation. No correlation was found between the Hveem stability values and those obtained for any of the other stability test procedures studied.

2. Some correlation was found between the cohesion as measured by the cohesiometer and the Marshall stability, the Texas Highway Department punching shear stability, the ultimate strength in direct compression, and the Asphalt Institute stability. The correlation was good in the case of the punching shear stability, fair in the case of the Marshall stability, and poor for the ultimate strength in direct compression and the Asphalt Institute stability.

3. Some correlation was found to exist between the Marshall stability, the Texas Highway Department punching shear, the ultimate strength in direct compression, and the Asphalt Institute stability. The correlation was rather good in the case of the Marshall stability, the punching shear stability, and the ultimate strength in direct compression. The correlation between the Asphalt Institute stability and the other three stability values was poor.

4. No correlation was found to exist between the modulus of elasticity in direct compression and any of the other stability values.

5. The Hveem stability depends primarily upon the characteristics of the aggregates except for those mixtures in which the voids are sufficiently low so that the asphalt acts as a lubricant. For well compacted mixtures with voids above approximately two per cent the Hveem stability is practically independent of the quantity of asphalt and the hardness of the asphalt.

6. Cohesion as measured by the cohesiometer increases with increasing asphalt content until the asphalt content is high enough to produce very low void or "fat" mixtures. Cohesion is also dependent upon the hardness of the asphalt cement used. The cohesion increases with increasing hardness of the

asphalt. No consistent relationship existed between the type of aggregate and the cohesion.

7. The Marshall stability, Texas Highway Department punching shear stability, ultimate strength and elastic limit in direct compression, and the Asphalt Institute stability all show the same type of variation in stability with variation in asphalt content for a given aggregate. The stability values rise to a peak at a given asphalt content and then fall. However, the maximum stability does not occur at the same asphalt content for the different test procedures. These stability values depend both on internal friction and on cohesion. The stability values rise with increasing cohesion and fall when the asphalt content is high enough to begin to lubricate the mixture and reduce internal friction.

8. The Marshall stability, the ultimate strength in direct compression, the Asphalt Institute stability, and the Hveem stability, based on maximum stability values, all indicated approximately the same differences in characteristics for the four aggregate combinations used in the laboratory hot-mix asphaltic concrete mixtures. This is true only for mixtures prepared with a given grade of asphalt cement by the Marshall compaction procedure.

9. The Marshall stability, Texas Highway Department punching shear stability, ultimate strength and elastic limit in direct compression, and the Asphalt Institute stability all vary with varying hardness of the asphalt cement. The stability values increase with increasing hardness of the asphalt cement thus reflecting the change in cohesion.

10. For mixtures with high internal friction the Marshall compaction procedure produced denser specimens than did the Asphalt Institute compaction procedure. The two procedures produced very nearly the same density for mixtures with low internal friction due either to the characteristics of the aggregate or to high asphalt content producing lubrication in the mixture.

11. For the limited number of mixtures studied the Texas Highway Department compaction procedure produced denser mixtures than did the Marshall or Asphalt Institute compaction procedures.

12. Comparison of stability values for specimens compacted by the Texas Highway Department compaction procedure with those compacted by the Marshall compaction procedure shows the following to be true.

(a) The Hveem stability is independent of the compaction procedure for mixtures with voids sufficiently high to eliminate the possibility of lubrication by the asphalt.

(b) The cohesion from the cohesiometer is higher for the Texas Highway Department procedure. This is probably due to the greater density produced by this procedure.

(c) The Marshall stability and Texas Highway Department punching shear stability values were higher for the Texas Highway Department compaction procedure. This is also probably due to the greater cohesion due to greater density.

(d) It is generally true that the ultimate strength and elastic limit in direct compression are higher for the Texas Highway Department compaction procedure.

13. The significant differences in density and in stability values obtained with differences in compaction procedures indicate that agreement on a compaction procedure is a primary need in the testing of asphaltic concrete mixtures.

REFERENCES

1. "Tentative Method of Test for Compressive Strength of Bituminous Mixtures." American Society of Testing Materials Standards, 1949. Page 1026.
2. "Manual on Hot-Mix Asphaltic Concrete Paving, Methods of Testing Mixtures, Stability." Asphalt Institute. Pages 30-39.
3. "Investigation of the Design and Control of Asphalt Paving Mixtures, Vol. 1, Inclosure II, Laboratory Test for Design of Asphalt Paving Mixtures." Corps of Engineers, Waterways Experiment Station, Technical Memorandum No. 3-254, 1948. Pages II-1, II-10.
4. "Care and Operation of the Hveem Stabilometer." Hogentogler and Co.
5. F. N. Hveem and R. M. Carmany. "Factors Underlying the Rational Design of Pavements." Proceedings Highway Research Board, Vol. 28, 1948. Page 101.
6. L. E. McCarty. "Applications of the Mohr Circle and Stress Triangle Diagrams to Test Data Taken with the Hveem Stabilometer." Proceedings Highway Research Board, Vol. 26, 1946. Pages 100-23.
7. "The Marshall Method for the Design and Control of Bituminous Paving Mixtures." Procedures for Design and Testing, Marshall Consulting and Testing Laboratory. Pages 17-23, 27-28.
8. "To Make the Stability or Shear Test." Texas Highway Department, Laboratory Handbook, November 1939. Page 80.
9. "Standard Methods of Test Procedures." Texas Highway Department, Construction Bulletin C-14, October 1947. Pages 12-26.
10. "Determining the Stability of a Molded Specimen of Asphaltic Concrete with the Hveem Stabilometer, THD-40." Texas Highway Department. 8 pages.
11. R. Vokac. "Compression Testing of Asphalt Paving Mixtures." Proceedings American Society for Testing Materials, Vol. 36, Part II, 1936. Pages 552-67.
12. R. Vokac. "Compression Testing of Asphalt Paving Mixtures." Proceedings American Society for Testing Materials, Vol. 37, Part II, 1937. Pages 509-18.

SELECTED BIBLIOGRAPHY

1. D. C. Broome and R. O. Child. "The Testing of Bituminous Mixtures." New York: Edward Arnold & Company. London: Longmans Green and Company, 1934.
2. W. H. Campen and J. R. Smith. "A Study of the Role of Angular Aggregates in the Development of Stability in Bituminous Mixtures." Proceedings Association of Asphalt Paving Technologists, Vol. 17, 1948. Page 114.
3. W. H. Campen and J. R. Smith. "A Study of the Omaha Testing Laboratories Bearing Index Test for Bituminous Mixtures." Proceedings Association of Asphalt Paving Technologists, Vol. 19, 1950. Page 369.
4. C. A. Carpenter, F. J. Goode, and R. A. Peck. "An Improved Triaxial Compression Cell for Testing Bituminous Paving Mixtures." PUBLIC ROADS, Vol. 26. No. 9. page 173. August 1951.
5. Ting Ye Chu and H. G. Spangler. "Plant Stability Test for Hot-Mix Asphaltic Concrete Mixtures." Proceedings Highway Research Board, Vol. 29, 1949. Page 159.
6. V. A. Endersby. "The Analytic Mechanical Testing of Bituminous Mixes." Proceedings Association of Asphalt Paving Technologists, Vol. 11, 1940. Page 158.
7. W. J. Emmons and B. A. Anderton. "A Stability Test for Bituminous Paving Mixtures." Proceedings A.S.T.M., Vol. 25, Part 2, 1925. Page 346.
8. A. T. Goldbeck, J. E. Gray, and L. L. Ludlow. "Laboratory Service Test for Pavement Materials." Proceedings A.S.T.M., Vol. 34, Part 2, 1934. Page 608.
9. W. O. B. Hillman. "Bending Tests of Bituminous Mixtures." PUBLIC ROADS, Vol. 21, page 69. June 1940.
10. H. T. Horsfield. "Strength of Asphalt Mixtures." JOURNAL SOCIETY CHEMICAL INDUSTRIES, Vol. 53, No. 16, page 107. April 1934.
11. P. Hubbard and F. C. Field. "A Practical Method of Determining the Relative Stability of Fine Aggregate Asphalt Paving Mix." Proceedings A.S.T.M., Vol. 25, Part 2, 1925. Page 335.
12. P. Hubbard and F. C. Field. "Correlation of Stability Test with Behavior of Pavement Under Traffic." ROADS AND STREETS, Vol. 67, page 52. January 1927.

13. P. Hubbard and F. C. Field. "Adaption of Stability Test to Include Coarse Aggregate Asphalt Paving Mixtures." ENGINEERING AND CONTRACTING, Vol. 71, No. 6, page 160. June 1932.

14. A. R. Lee and A. H. D. Markwick. "The Mechanical Properties of Bituminous Surfacing Materials Under Constant Stress." JOURNAL SOCIETY CHEMICAL INDUSTRIES, Vol. 56, page 146 T. May 1937.

15. A. R. Lee and P. J. Rigden. "Use of Mechanical Tests in Design of Bituminous Road Surfacing Mixtures—Dense Tar Surfacings." JOURNAL SOCIETY CHEMICAL INDUSTRIES, Vol. 64, No. 6, page 153 T. June 1945.

16. C. Mack. "Study of Bituminous Mixtures on Road Testing Machine." JOURNAL SOCIETY CHEMICAL INDUSTRIES, Vol. 60, page 111 T. May 1941.

17. B. C. Manton and W. G. Wren. "Mechanical Testing of Plastic Road Materials." JOURNAL SOCIETY CHEMICAL INDUSTRIES, Vol. 53, No. 20, page 141 T. May 1934.

18. Gayle McFadden and W. C. Ricketts. "Design and Field Control of Asphalt Paving Mixtures for Military Installations." Proceedings Association of Asphalt Paving Technologists, Vol. 17, 1948. Page 93.

19. N. W. McLeod. "The Stability of Granular and Cohesive Materials in Triaxial Compression." Association of Asphalt Paving Technologists, Vol. 17, 1948. Page 184.

20. L. W. Nijboer. "Mechanical Stability of Bitumen Aggregate Mixtures." JOURNAL SOCIETY CHEMICAL INDUSTRIES, Vol. 67, No. 6, page 244 T. June 1948.

21. J. T. Pauls. "Dimensions of Testing Equipment Affect Hubbard Field Stability Values." PUBLIC ROADS, Vol. 17, page 38. April 1936.

22. J. T. Pauls and H. M. Rex. "A Test for Determining the Effect of Water on Bituminous Mixtures." PUBLIC ROADS, Vol. 24, No. 5, page 115. July 1945.

23. J. P. Pfeiffer. "Observations on Mechanical Testing of Bituminous Road Mixtures." JOURNAL SOCIETY CHEMICAL INDUSTRIES, Vol. 57, No. 7, page 213 T. July 1938.

24. H. W. Skidmore. "Practical Application of the Shear Test to Bituminous Mixtures." ROADS AND STREETS, Vol. 69, No. 1, page 5. January 1929.

25. F. P. Smith. "Stability of Asphalt Pavements." ROADS AND STREETS, Vol. 68, No. 2, page 115. February 1928.

26. V. R. Smith. "Triaxial Stability Method for Flexible Pavement Design." Proceedings Association of Asphalt Paving Technologists, Vol. 18, 1949. Page 63.

27. T. E. Stanton and F. N. Hveem. "Role of the Laboratory in the Preliminary Investigation and Control of Materials for Low Cost Bituminous Pavements." Proceedings Highway Research Board, Vol. 14, Part II, 1934. Page 14.

28. T. E. Stanton and F. N. Hveem. "Measuring Stability and Cohesion of Bituminous Paving Mixtures by Machines." CALIFORNIA HIGHWAYS AND PUBLIC WORKS, page 10. January 1936.

29. E. L. Tarwater. "Roller Testing Machine for Measuring Stability of Bituminous Mixtures." PUBLIC ROADS, Vol. 16, No. 7, page 134. September 1935.

30. N. H. Taylor. "Design and Testing of Asphalt Paving Mixtures." JOURNAL SOCIETY CHEMICAL INDUSTRIES, Vol. 51, No. 53, page 415 T. December 1932.

31. R. Vokac. "An Impact Test for Studying Characteristics of Asphalt." Proceedings Association of Asphalt Paving Technologists, Vol. 6, 1935. Page 40.

32. M. C. Warner. "Wyoming Laboratory Test for Stability of Oil Mix." WESTERN CONSTRUCTION NEWS, page 364. November 1939.

PREVIOUS BULLETINS OF THE TEXAS ENGINEERING EXPERIMENT STATION

Numbers 1 to 46 published 1915 to 1939. List furnished on request.

No. 46. Rural Water Supply and Sewerage. Part 1. Excreta Disposal and Sewerage. E. W. Steel and P. J. A. Zeller. 1939.

No. 47. Treatment of Settled Sewage in Lakes. F. E. Giesecke and P. J. A. Zeller. 1939.

*No. 48. Lecture Notes on Practical Petroleum Geophysics. Garrett Kemp. 1940.

*No. 49. Papers Presented at the First Annual Air Conditioning Short Course. 1939.

No. 50. A Rational Method of Analyzing Water Rate Structures. S. R. Wright. 1940.

No. 51. Rural Water Supply and Sewerage. Part II, Rural Water Supply. E. W. Steel and P. J. A. Zeller. 1940.

No. 52. The Installation and Use of Attic Fans. W. H. Badgett. 1940.

No. 53. Proceedings of the Sixteenth Annual Short Course in Highway Engineering. 1941.

No. 54. The Willard Chevalier Lectures. 1940.

No. 55. The Effect of Voltage Variations on the Domestic Consumer. L. M. Haupt, Jr. 1940.

No. 56. Proceedings of the First Annual Conference on Surveying and Mapping, May 1940. 1941.

No. 57. A History of Suspension Bridges in Bibliographical Form. A. A. Jakkula. 1941.

No. 58. Two-Span Continuous Beams with Dead Loads. A. A. Jakkula. 1941.

No. 59. Space for Teaching. An Approach to the Design of Elementary Schools for Texas. W. W. Caudill. 1941.

No. 60. Proceedings of the First and Second Annual Conference of Municipal Engineers. 1941.

No. 61. Proceedings of the Conference on Highway Economics. 1941.

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No. 64. Solution of Two-Span Continuous Beams Under Live Loads by use of Nomographs. A. A. Jakkula. 1941.

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*No. 66. Some Fundamentals of Timber Design. Howard J. Hansen. 1942.

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