A LABORATORY STUDY OF THE OPERATOR VARIABLE ON MOLDING PROCEDURE AND MIX DESIGN VARIATIONS IN HOT-MIX ASPHALTIC CONCRETE

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CONTENTS

SUMMARY

This study was conducted in an effort to measure the effect of differences in the amount and intensity of laboratory compactive effort on the densification of selected but distinctly different asphaltic concrete mixtures.

The nature of the Texas gyratory shear method of molding laboratory test specimens is such that one may expect differences in specimen densification for different operators. A number of different operators were used in this program and a statistical analysis was performed on the data from selected operators. The results from this portion of the study are presented in terms of the standard deviation, s, and the coefficient of variation, C.V.

More specifically the program of study was concerned with the following items:

(1) To determine how well a given operator of limited training repeated test specimen densities for given designs and materials,

(2) To determine whether or not the physical characteristics of asphaltic concrete made from widely different types of materials affected an operator's ability to repeat test specimen densities,

(3) To determine how well different operators reproduce the test specimen density results of other operators working with the same materials and equipment, and

(4) To determine, in general, the effect of changing Texas' standard molding and testing procedures on the results of the Hveem stabilometer and cohesiometer values.

CONCLUSIONS

The following conclusions appear to be generally justified based on the materials, designs, operators, and equipment used in this program:

1. For the asphaltic concrete of Phase I made completely of rounded particles and a low penetration asphalt cement, the THD procedure of molding produced higher Hveem stabilities and lower bulk densities than those obtained by other methods of densification used in this study. Highest densities and highest cohesiometer values were obtained at 40 gyrations applied at a constant foot pressure of 31 psi.[1] Intraparticle attrition and better nesting of aggregates may account for this apparent improvement of the cohesiometer values.

2. In Phase II of the program nine operators were used and not only were the foot pressure and number of gyrations varied but also the leveling pressure was changed. The sandstone aggregates used in Phase II had a high abrasion loss and were degraded materially during molding. The data show that the highest bulk densities were obtained from specimens molded by Standard THD Procedures. Apparently higher levels of compaction energy produced greater voids by unusual degradation of the aggregates as discussed later in this report. At a fixed leveling pressure of 1590 psi and variable gyrations from 20 to 50, the Hveem stability and cohesion presented no pattern within operator variability even though stability ranged from 41 to 63 and cohesion from 178 to 522.

However, for a fixed foot pressure and fixed number of gyrations and variable leveling pressure, there was a definite peaking in the cohesiometer values obtained. The peak occurred at 2750 psi leveling pressure and 30 gyrations at a foot pressure of 31 psi. Bulk densities of the molded specimens did not correlate with energy of compaction.

3. The aggregate combination used in Phase III of the study contained 85 percent rounded material and 15 percent crushed stone with a medium high absorption value. If those specimens molded by THD procedures are omitted the bulk specific gravity is seen to vary directly with increased

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[1] This foot pressure of 31 psi is a calculated value based on a hydraulic ram pressure of 50 psi and assumes an even distribution of pressure at the interface between the upper ram and the specimen.

energy of compaction. By comparing results of the cohesiometer values listed in the two tables it appears that the effect of operator variability is more pronounced than is variation in energy of compaction for this mix design.

4. Operator reproducibility is often affected by the nature of the materials and design of an asphaltic concrete mixture. The aggregates used in Phase IV were dense and rounded except for 16 percent which was a crushed sandstone of high absorption. Both the density and the Hveem stability are apparently unaffected by differences in compaction procedure and operator technique. As was the case with other mixes studied the cohesiometer values increased with compactive effort. It is suggested that a mix of this type might be improved in stability by added compaction if the Marshall method of design were used, since Hveem cohesion and Marshall stability correlate reasonably well.

5. When molded by two different operators, the gap graded mix of Phase V showed excellent reproducibility and repeatability in test values. For a variation of compaction energy of more than threefold in the five levels used there was a remarkably small variation in Hveem stability. For sixty specimens the range was from 38 to 43. This would indicate a limiting stability exists for the materials and mix design. It further appears that where differences in laboratory compaction energy produce maximum values in both Hveem cohesion and stability that there are separate and distinct levels of compaction energy producing maximum stability in one case and maximum cohesion in the other.

One possible explanation for an increase in cohesion with increasing energy of compaction is the production of an asphalt mastic on the aggregate surface by intraparticle attrition. For the mixes studied this appears valid for those mixes that might be expected to produce very fine particles during compaction. This explanation does not appear to apply for materials that granulate under stress such as sandstone. If excessive fines are produced by this attrition process, the cohesiometer value may be expected to drop.

6. Where differences in operator stamina and physical strength are apparent, the THD standard molding procedure may produce specimens with the most consistent stability values. With the other variations in compaction energy used in this study the operator of least strength and stamina produced test specimens of the lowest density but of the highest stability.

For the material and design used in Phase VI the operator variable affected the cohesiometer values more than did the differences in energy of compaction. Averages of cohesiometer values for different operators and energies of compaction ranged from 225 to 366. Yet the cohesiometer values peaked for each operator but at different levels of compaction energy and it might be further added that this peaking was also a function of operator stamina and strength.

7. Differences in test specimens created by different operators and with different amounts of compaction energy have a materially greater affect on test results than investigated variations in the Texas testing procedure.

8. Specimen density variability is reduced for a given mix design by using a compaction procedure consisting of a fixed number of gyrations and a constant foot and leveling pressure when compared to THD standard procedures of compaction.

9. Hveem stability variations do not appear to correlate with compaction method or density for all the mixtures studied; however, for these same mixes Hveem stability can normally be expected to be within plus or minus ten percent of the mean value two out of three times.

A Laboratory Study of the Operator Variable on Molding Procedure and Mix Design Variations in Hot-Mix Asphaltic Concrete

Introduction

This study was concerned primarily with laboratory evaluations of job mixed formulations of hot-mix asphaltic concrete taken from regular contract work in District 17 of the Texas Highway Department and molded by different operators using planned variations of the THD Standard molding procedure.

Texas Highway Department Test Method Tex-206-F, Method of Compacting Test Specimens of Bituminous Mixtures," is described in Volume I —— Manual of Testing Procedures published in June 1962 by the Texas Highway Department. Also described in this same volume are Test Method Tex-208-F and Test Method Tex-214-F which deal with the Hveem stability and cohesion tests respectively. The procedures outlined in these tests were used in this research with variations that will be described as the data are presented.

The general objectives of the series of tests were (1) to determine how well a given operator of limited training repeated test specimen densities in given designs and materials, (2) to determine whether or not the physical characteristics of asphaltic concrete made from widely different types of materials affected an operator's ability to repeat test specimen densities, (3) to determine how well different operators reproduce the test specimen density results of other operators working with the same materials and equipment, and (4) to determine, in general, the effect of changing Texas' standard molding and testing procedures on results of the Hveem stabilometer and cohesiometer values.

In January of 1962 the Texas Transportation Institute presented the results of "A Study of Hveem Stability versus Specimen Height" before the Highway Research Board. In this study it was found, among other things, that measured Hveem stability of dense-graded asphaltic concrete varies linearly with the height of the test specimen. It was also pointed out in this study that the THD method of compacting test specimens automatically controls the compactive effort so that specimens of various heights have almost identical densities provided materials and design are fixed and the same operator does all the compacting with the same equipment.

This last point has an important bearing on the present study because in actual field operations where mix designs are being controlled, it is important to know possible sources of error or differences in test specimens. There are, of course, situations where small differences in stability or cohesioeter values are of no consequence; however, if the materials and design produce borderline values, knowledge of possible sources of error becomes important.

The data and discussions to follow may be of assistance in the laboratory and the field in use and interpretation of similar data.

Since aggregate grading, shape of particle, and surface texture have their very definite effects on the laboratory performance and general test results, the description of the materials used in the different phases of the research will accompany the physical descriptions and laboratory test results associated with these materials.

PHASE I

Materials

A variety of aggregates was used in the experimental work. The materials included a wet bottom boiler slag made from burning lignite, a well rounded river gravel, crushed limestone, crushed sandstone, crusher fines from both limestone and sandstone, natural river sand, field sand, and fly ash.

The physical characteristics of these materials are described by tabulated data, figures, and discussions to follow.

Figure 1 shows the grading of an all rounded aggregate blend made from Gifford Hill silicious gravel and sand combined with a fly ash produced from burning lignite. These materials were proportioned to approximate Fuller's density for the particle size distribution involved. Also included in Figure 1 is a typical aggregate gradation analysis of an extracted test specimen. Very little change in grading is apparent, especially if one considers the normal variation in samples that is encountered in such operations. These aggregates are quite hard and the coarse fraction has a Los Angeles abrasion loss of about 25 percent and a water absorption of one percent.

The centrifuge kerosene equivalent (California Test Method 303-B) was used to establish the optimum asphalt content of 3.5% for this blend of aggregates. A 50-60 penetration asphalt produced from selected crudes was used. The mixing temperature selected for use in this blend was that temperature at which the asphalt cement was considered to have a Saybolt Furol viscosity of 100 seconds. Molding operations for this blend as well as that of all other combinations used in the entire study were carried out at 250 $\pm$ 5°F in molding equipment that had been preheated to 200 $\pm$ 10°F.

Variable Compactive Effort with Different Operators

Shown in Table 1 are molding data from nine different operators. Column two of these data indicates the factor of variability in the compactive effort used in forming these specimens. The regular Texas Highway Department gyratory shear compactor was used with one modification. By connecting a hydraulic line to the pressure side of the hydraulic jack used with the apparatus, it was possible to set the jack ram at a selected and fixed pressure. A selected and constant jack ram pressure or compactor foot pressure was made possible by the use of compressed air and an air pressure regulator.

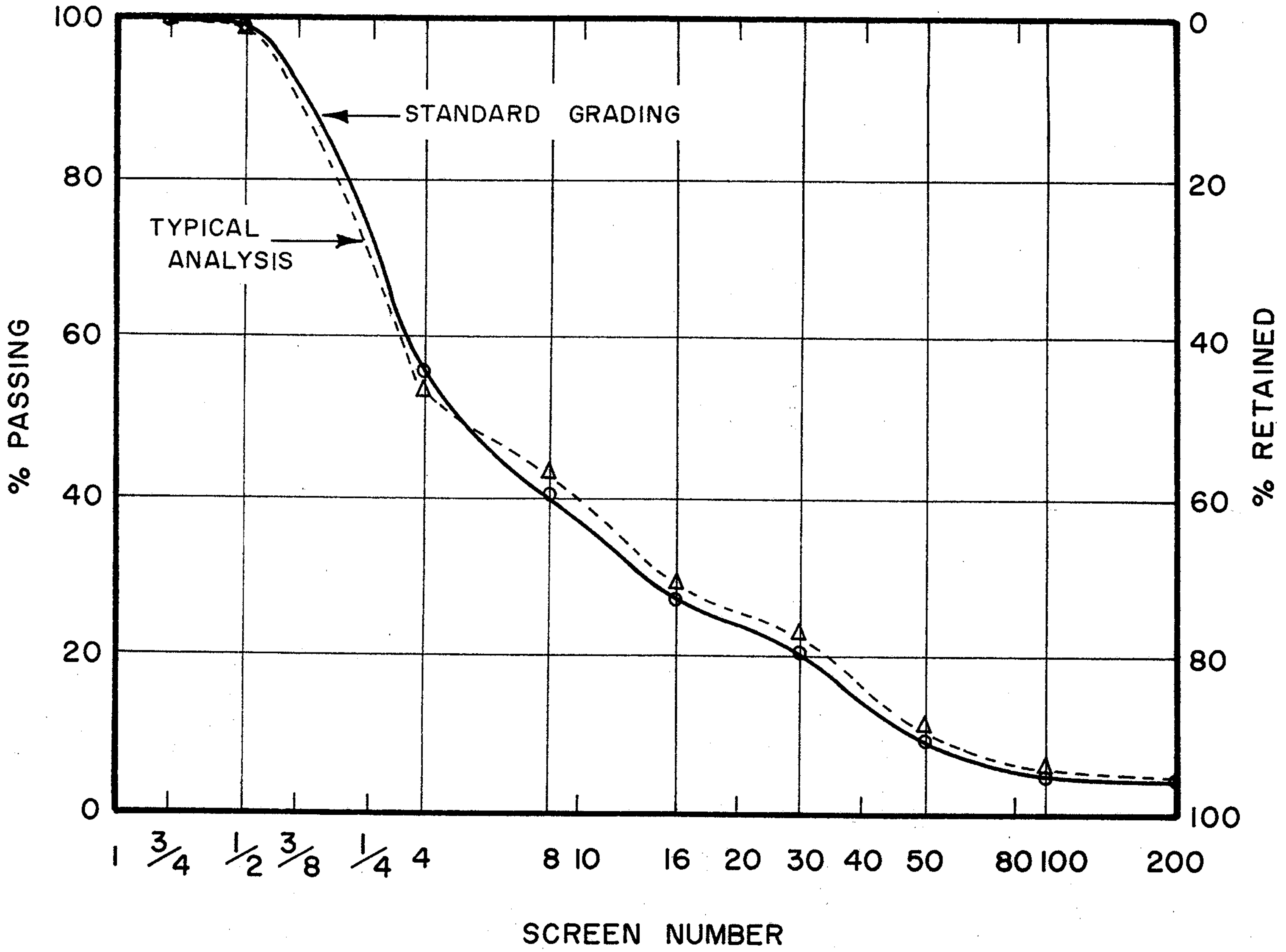

100
80
60
40
20
0
% PASSING
0
20
40
60
80
100
% RETAINED
STANDARD GRADING
TYPICAL ANALYSIS
1
3/4
1/2
3/8
1/4
4
8
10
16
20
30
40
50
80
100
200
SCREEN NUMBER

FIGURE 1

TABLE 1

Laboratory Results of Modified Molding Procedures

Gifford Hill Gravel, Concrete Sand, and Fly Ash
Graded to Fuller's Density, 3.5 Percent - 50-60 Pen. Asphalt

Sample No.	Number of Gyrations	Operator	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	Foot Press psi	Leveling Press. psi
A	10	RG	2.445	30	441	31	1590
B	10	RG	2.464	34	510	31	1590
C	10	RG	2.453	28	406	31	1590
A	20	x	2.463	41	408	31	1590
B	20	x	2.465	35	410	31	1590
C	20	x	2.466	40	320	31	1590
D	20	x	2.472	27	420	31	1590
E	20	x	2.476	29	383	31	1590
F	20	x	2.470	31	383	31	1590
A	20	RL	2.454	31	332	31	1590
B	20	RL	2.457	40	324	31	1590
C	20	RL	2.436	39	379	31	1590
D	20	RL	2.447	40	387	31	1590
E	20	RL	2.439	34	370	31	1590
A	20	RH	2.445	31	---	31	1590
B	20	RH	2.445	30	622	31	1590
C	20	RH	2.435	32	484	31	1590
D	20	RH	2.435	29	460	31	1590
E	20	WFW	2.445	30	541	31	1590
F	20	WFW	2.450	30	506	31	1590
G	20	WFW	2.445	29	497	31	1590
H	20	WFW	2.445	30	570	31	1590
A	30	x	2.473	30	446	31	1590
B	30	x	2.481	32	354	31	1590
C	30	x	2.481	34	415	31	1590
D	30	x	2.461	31	394	31	1590
E	30	x	2.468	29	441	31	1590
F	30	x	2.468	30	446	31	1590
A	30	RH	2.460	28	311	31	1590
B	30	RH	2.460	25	346	31	1590
C	30	RH	2.465	33	367	31	1590
D	30	RH	2.455	27	297	31	1590
E	30	KK	2.465	37	565	31	1590
F	30	KK	2.460	30	565	31	1590
G	30	KK	2.470	29	545	31	1590
H	30	KK	2.458	35	576	31	1590

TABLE (Cont.)

Sample No.	Number of Gyrations	Operator	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	Foot Press, psi	Leveling Press. psi
A	40	RAJ	2.477	27	645	31	1590
B	40	RAJ	2.475	29	594	31	1590
C	40	RAJ	2.485	34	634	31	1590
D	40	RAJ	2.475	36	635	31	1590
E	40	RH	2.460	36	678	31	1590
F	40	RH	2.465	35	675	31	1590
G	40	RH	2.458	36	566	31	1590
H	40	RH	2.455	36	554	31	1590
A	50	RAJ	2.475	35	608	31	1590
B	50	RAJ	2.465	30	313	31	1590
C	50	RAJ	2.470	32	465	31	1590
D	50	RH	2.455	40	622	31	1590
E	50	RH	2.455	42	538	31	1590
F	50	RH	2.463	43	564	31	1590
G	50	RH	2.465	36	612	31	1590
H	50	RH	2.455	37	517	31	1590
I	50	RH	2.450	39	586	31	1590
J	50	RH	2.455	30	522	31	1590
A	THD 18	LAW	2.290	38	334	Varied	1590
B	THD 12	LAW	2.298	47	305	Varied	1590
C	THD 15	LAW	2.288	40	287	Varied	1590
D	THD 12	WWS	2.319	41	298	Varied	1590
E	THD 18	WWS	2.272	45	328	Varied	1590
A	THD	RH	2.440	37	490	Varied	1590
B	THD	RH	2.422	39	423	Varied	1590
C	THD	RH	2.438	32	448	Varied	1590
D	THD	RH	2.430	29	461	Varied	1590
E	THD	RH	2.430	28	486	Varied	1590
F	THD	RH	2.410	34	468	Varied	1590

The apparatus as modified is shown in Figure 2. With this arrangement it is possible to maintain a constant jack ram pressure at selected pressures within the capability of available air pressures. For this series of tests the ram pressure selected was 50 psi. This pressure on the ram produced an effective foot pressure of about 31 psi on the specimen being compacted and is the beginning pressure used in the standard method of compaction used by THD. As a control or reference, three of the operators compacted test specimens of this mix using the regular THD procedure. When the regular THD compaction procedure was used a valve on the line leading to the air regulator was closed. Data on specimens molded according to standard THD procedures are also included in Table 1 and occur at the end of the listings. It is to be noted in column two that a number follows the designation THD for the first five specimens. This represents the number of gyrations required to develop the required internal resistance called for by the compaction procedure. In column seven the foot pressure is listed as "varied". This is a natural result of the standard procedure which requires development of an equivalent 31 psi average foot pressure and then inducing three gyrations allowing the foot pressure to seek its own level. It must be realized that actual contact pressures between the foot and the mix may be very much higher than 31 psi. Quite often in the early stages of the compaction process the foot pressure drops almost to zero during the first gyration but still three complete gyrations are performed before the foot pressure is again raised to 31 psi which is equivalent to 50 psi gage on the hydraulic jack specified. All operators used the same molding equipment but none of the operators molded specimens at all compaction energy levels in this phase of the study. The primary reason for this is evident from the density data shown in Table 1. The particular mix in question is sensitive to differences in compactive effort as is clearly shown by density values but it is also sensitive to difference in operator technique even though each operator supposedly followed the same procedure.

It is interesting to note that the average of the densities obtained from compaction with 10 gyrations and 31 psi constant foot pressure is higher than that obtained when similar specimens were compacted by as many as 18 gyrations applied in accordance with THD standard procedures. The effect of these two methods of compaction on the test results is not apparent from the data; however, if one examines the test data on the specimens compacted at 20, 30, 40, and 50 gyrations and a constant foot pressure of 31 psi, it is evident that the cohesiometer value is essentially constant for specimens molded at 20 and 30 gyrations and a fixed foot pressure but increases materially at 40 gyrations. This value is decreased at 50 gyrations.

This would appear to indicate that for this particular mix there is an optimum effective compaction energy resulting from this modified procedure that will produce maximum cohesiometer values. This increase probably results

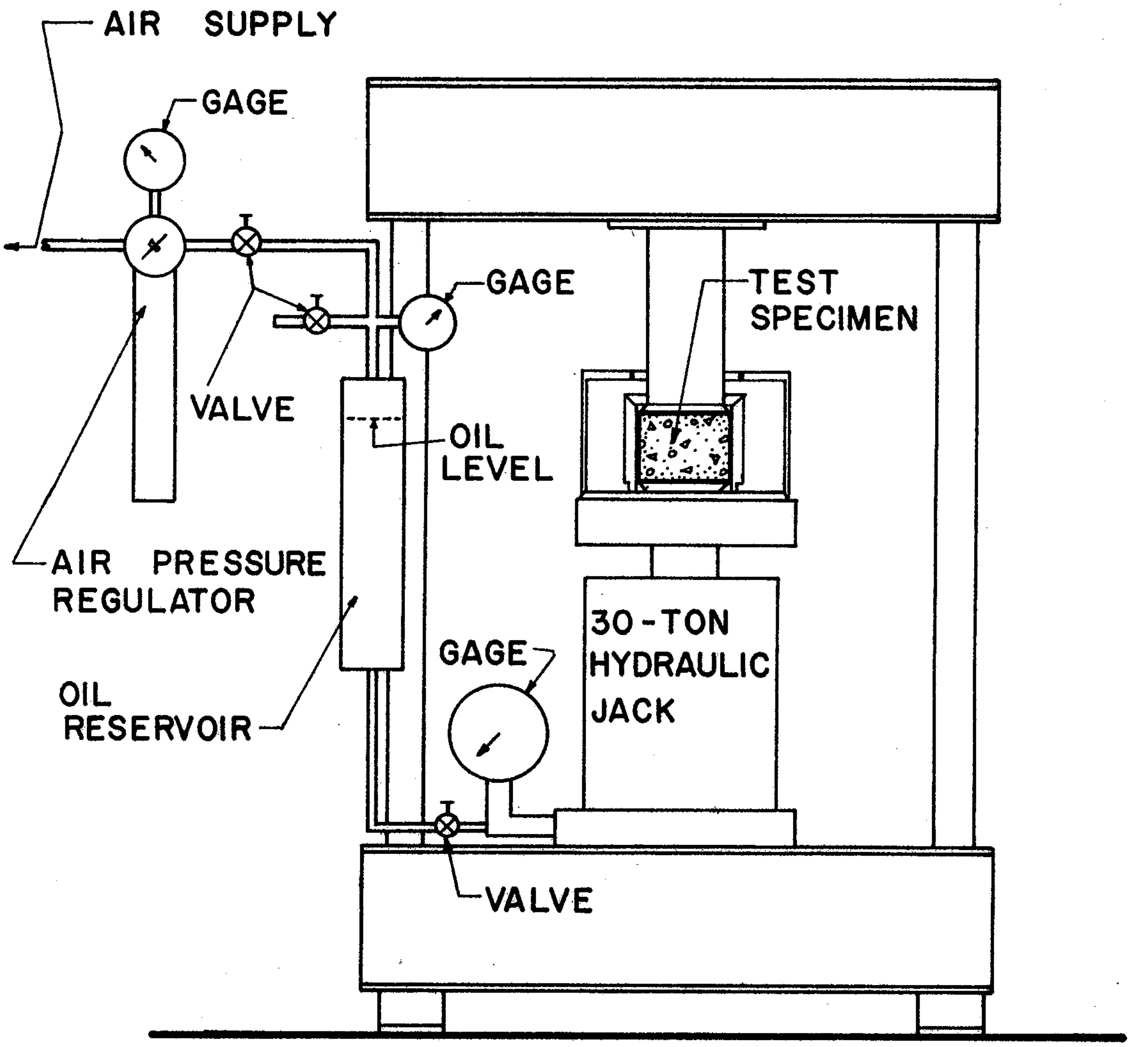

AIR SUPPLY
GAGE
GAGE
TEST SPECIMEN
VALVE
OIL LEVEL
AIR PRESSURE REGULATOR
OIL RESERVOIR
GAGE
30-TON HYDRAULIC JACK
VALVE

FIGURE 2

from better nesting of the aggregate used in this phase of the study.

Variation in the averages of the Hveem stabilities is small with the range of values from 31 to 37. The specimens compacted by THD standard procedures produced the highest average value. The reason for this, if it be real, is not apparent unless intraparticle attrition is a factor.

PHASE II

Materials

The materials used in the second phase of the study are described in Figure 3 and Table 2 and were obtained from the finishing machine on the job. The job in question dealt with a hot-mix asphaltic concrete overlay on Texas State Highway No. 6 within the city limits of Bryan and College Station, Texas. As was the case in Phase I these materials were blended to meet the general requirements of a dense graded surface course mix with a top size aggregate of about one-half inch. The sandstone as indicated in Table 2 has a low specific gravity and the combination of materials produced a theoretical specific gravity of only 2.015. The high water absorption and high Los Angeles abrasion wear of this sandstone was in marked contrast to the low values of the siliceous river gravel of Phase I.

Variable Compaction Energy and Different Operators

Table 3 lists the laboratory data obtained on the sandstone mixture. In Phase I the leveling pressure used was constant at 1590 psi for all test specimens and this is the pressure intensity required in THD Standard Procedures. Reference to the data on these specimens indicates that the average density of specimens molded by standard procedures is higher than any of those obtained by the other methods. The explanation for this may be that unusual degradation caused by the more severe molding stresses created higher voids in the finished specimen. It is again pointed out that the material used (sandstone) had a high loss in the Los Angeles abrasion test. It is interesting to note that the Hveem stability and cohesion values of these specimens are definitely lower than corresponding values for specimens molded by the other procedures. A similar result was evident in Phase I for the cohesiometer value but not for stability.

For a fixed leveling pressure of 1590 psi, the number of gyrations over the range of 20 to 50 appeared to have little effect on either the stability or cohesion within operator variability. Although extreme values of stability were 41 and 63 and similar values for cohesion were 178 to 522, no pattern is apparent from the data.

For the number of gyrations fixed at 30 and the leveling pressure varied from 1590 to 3060 psi, the pattern of variation in the cohesiometer value was more or less similar to that obtained in Phase I where only the number of gyrations was varied. The cohesiometer value peaked at a leveling pressure of 2750 psi then dropped at the next higher leveling pressure. For this particular material and mix design there is no correla-

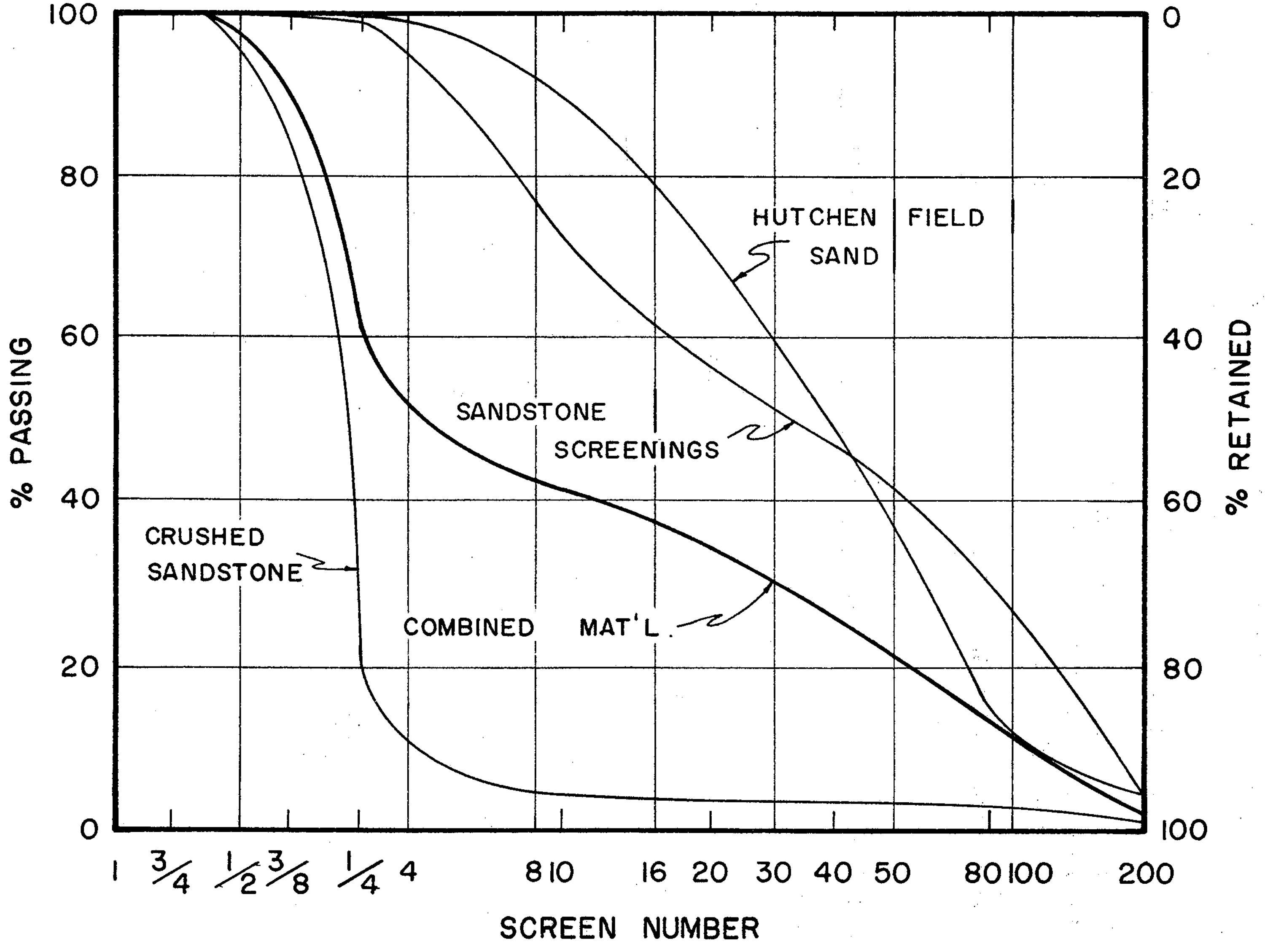

100
80
60
40
20
0
0
20
40
60
80
100
% PASSING
% RETAINED
HUTCHEN FIELD SAND
SANDSTONE SCREENINGS
CRUSHED SANDSTONE
COMBINED MAT'L.
1
3/4
1/2
3/8
1/4
4
8
10
16
20
30
40
50
80
100
200
SCREEN NUMBER

FIGURE 3

TABLE 2

Design Values for Mix From SH 6 and FM 60

Aggregates	Specific Gravity
50.0% Crushed Varisco Sandstone	1.934
30.0% Varisco Sandstone Screenings	2.386
20.0% Hutchen Field Sand	2.602
85-100 Penetration Asphalt	1.003

Asphalt Content, %	Hveem Stability, %	Voids, %
4.0	41	9.0
4.9	46	6.8
5.8	46	4.5
6.6	46	2.8
7.5	50	0.7

Theoretical Specific Gravity

$$\text{Aggregate, } G = \frac{100}{\frac{50}{1.934} + \frac{30}{2.386} + \frac{20}{2.602}} = 2.168$$

$$\text{Mix, } G_T = \frac{100}{\frac{93.5}{Y} + \frac{6.5}{1.003}} = 2.015$$

tion between the laboratory test results and the specimen density within the bounds of compaction energies used.

In an over-all analysis of the data in Table 3 the reader is cautioned to disregard test values that are obviously out of line, particularly low values since these are most likely the result of damaged specimens. All values were included in the tabulation to show a true picture of normal laboratory operations. Too often the data shown in a report have been reduced and for those not well informed in the area, this can be quite misleading to say the least. In many field control operations involving similar testing programs there is a sizeable turn-over in employees, so in a contract extending over several months the operator variability pattern could well be strikingly similar to that shown in these data. Knowledge of these variations may be quite important under certain circumstances.

TABLE 3

Laboratory Results of Modified Moldings Procedures

31 psi Constant Foot Pressure and Variable Leveling Load
THD Type D Class A Hot-Mix from State Highway 6 and F.M. 60

Sample No.	Number of Gyrations	Operator	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	Leveling Pressure, psi
A	20	RH	1.948	50	298	1590
B	20	RH	1.955	47	244	"
A	30	RH	1.970	51	440	"
B	30	RH	2.001	55	442	"
C	30	RH	1.955	50	292	"
D	30	RH	1.971	60	267	"
A	30	RAJ	1.985	56	404	"
B	30	RAJ	1.982	46	452	"
A	30	WWS	1.988	59	400	"
B	30	WWS	1.991	47	522	"
A	40	RH	2.021	61	215	"
B	40	RH	1.979	60	230	"
C	40	RH	1.950	41	322	"
D	40	RH	1.958	45	211	"
A	40	MS	1.965	63	227	"
B	40	MS	1.999	62	240	"
A	40	RAJ	1.942	52	178	"
B	40	RAJ	1.950	54	322	"
A	50	RH	1.995	46	493	"
B	50	RH	1.995	52	445	"
C	50	RH	1.991	51	206	"
D	50	RH	2.001	53	356	"
A	30	RH	1.959	58	207	1830
B	30	RH	1.955	57	140	"
C	30	RH	1.968	63	226	"
A	30	RH	1.985	71	245	2440
B	30	RH	1.979	61	162	"
C	30	RH	1.985	57	205	"
A	30	CWL	1.994	57	242	2750
B	30	CWL	1.980	62	273	"
C	30	CWL	2.010	57	273	"
D	30	CWL	2.031	52	324	"
E	30	CWL	2.020	66	298	"
F	30	CWL	2.025	49	375	"

TABLE 3 (Cont.)

Sample No.	Number of Gyrations	Operator	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	Leveling Pressure, psi
A	30	BCM	2.020	52	288	2750
B	30	BCM	2.025	63	387	"
C	30	BCM	2.031	49	509	"
D	30	BCM	2.025	62	404	"
A	30	RAJ	1.995	58	386	"
B	30	RAJ	1.990	67	525	"
C	30	RAJ	2.050	65	348	"
A	30	WFW	1.975	67	575	"
B	30	WFW	1.975	61	570	"
C	30	WFW	1.965	61	612	"
A	30	HKK	1.980	69	586	"
B	30	HKK	1.980	68	690	"
C	30	HKK	1.970	68	690	"
A	30	RH	2.000	67	185	3060
B	30	RH	1.993	58	195	"
C	30	RH	1.993	62	201	"
A	30	CWL	2.005	67	327	"
B	30	CWL	1.987	52	186	"
C	30	CWL	1.986	59	253	"
A	THD*	RH	1.990	60	370	1590
B	THD	RH	1.995	60	348	"
C	THD	RH	1.990	44	279	"
D	THD	RH	1.989	55	271	"
E	THD	RH	2.036	46	245	"
F	THD	RH	2.023	43	222	"
G	THD	RH	2.006	43	153	"
H	THD	RH	2.051	58	158	"
I	THD	RH	2.035	49	102	"
J	THD	RH	2.051	45	125	"
K	THD	RH	2.039	49	150	"
L	THD	RH	2.010	49	152	"
A	THD	Y	2.072	37	95	"
B	THD	Y	2.075	39	228	"
C	THD	Y	2.065	39	107	"
A	THD	HKK	2.039	43	171	"
B	THD	HKK	2.039	47	246	"
C	THD	HKK	2.035	51	248	"
D	THD	HKK	2.025	58	265	"
E	THD	HKK	2.039	58	274	"

*Note: All specimens compacted according to THD procedure were gyrated a variable number of times and the initial foot pressure was 31.

PHASE III

Materials

Where it is practical, local materials are used to the greatest extent possible, provided such materials meet specification requirements and produce a suitable job mix formulation. Such was the case for the hot-mix asphaltic concrete used in Phase III of this study. The mix in question was taken from the finishing machine on an overlay job in District 17 of the Texas Highway Department and delivered to the laboratory for molding and testing.

Shown in Figure 4 are the individual grading curves for the materials used in the formulation as well as the grading curve for the combined material. Table 4 lists the physical characteristics of these materials and typical values of stability and final voids for asphalt-aggregate combinations. The crusher fines used in the mix have a high absorption value whereas the other materials have an absorption value of approximately one percent. This is pointed out here to explain why some of the bulk specific gravities shown in Table 5 exceed the theoretical specific gravity of the mix as shown in Table 4. The data in Table 4 were supplied by the THD District Laboratory. Laboratory procedures used in obtaining these data neglect the absorption factor so the reader is cautioned against concluding that those specimens in Table 5 with bulk specific gravities equal to or slightly in excess of the theoretical represent erroneous data. As a matter of fact, at the 4.3 percent asphalt content used, these mixes would produce laboratory specimens with 3 to 4 percent voids when compacted by THD Standard Procedures. If absorption were considered, the true value of the voids would be higher and the difference in the real and THD values would be a function of the magnitude of the asphalt absorption. For highly absorptive aggregates the difference is appreciable; whereas, for hard dense aggregates the difference is negligible.

Variable Compaction Energy with Different Operators

In this phase of the research a total of four operators and five different levels of compaction energy were used. Each operator prepared test specimens following THD Standard Procedures and then proceeded to vary the energy as shown in Tables 5 and 6. As may be seen from the averages of all the data, an increase of compaction energy resulted in an increase in bulk specific gravity; it is assumed that the actual energy of compaction in the THD method was somewhat more than that produced by 30 gyrations, a constant foot pressure of 19 psi and a leveling pressure of 1590 psi. This

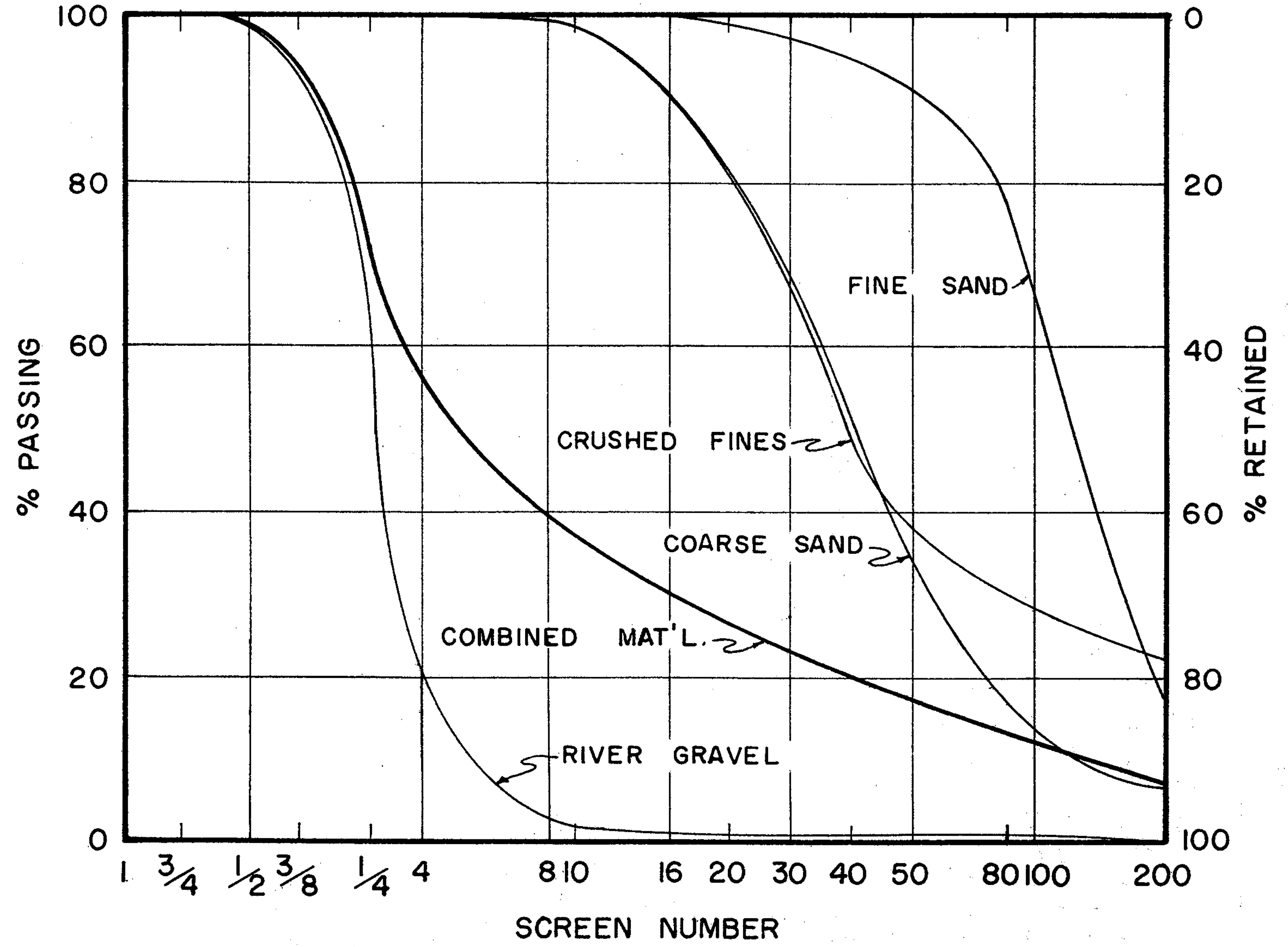

100
80
60
40
20
0
% PASSING
0
20
40
60
80
100
% RETAINED
1
3/4
1/2
3/8
1/4
4
8
10
16
20
30
40
50
80
100
200
SCREEN NUMBER
FINE SAND
CRUSHED FINES
COARSE SAND
COMBINED MAT'L.
RIVER GRAVEL

FIGURE 4

TABLE 4

Design Values for Mix From SH 6 North

Aggregates	Specific Gravity
60.0% Gifford-Hill Gravel	2.607
15.0% Texas Crushed Stone	2.470
15.0% Coarse Field Sand	2.573
10.0% Fine Field Sand	2.573
85-100 Penetration Asphalt	0.990

Asphalt, %	Hveem Stability, %	Voids, %
3.5	36	5.7
4.0	39	4.3
4.5	37	3.0
5.0	32	1.4
5.5	29	0.3

Theoretical Specific Gravity

$$\text{Aggregate, } G = \frac{100}{\frac{60}{2.607} + \frac{15}{2.470} + \frac{25}{2.573}} = 2.577$$

$$\text{Mix } G_T = \frac{100}{\frac{95.7}{Y} + \frac{4.3}{0.990}} = 2.410$$

TABLE 5

Laboratory Results of Modified Molding Procedures THD Type D Hot Mix, River Gravel, Crushed Limestone, and Field Sand - Leveling Pressure 1590 psi

	THD Standard				19 psi 30 Gyrations				19 psi 40 Gyrations			
		Bulk	Hveem			Bulk	Hveem			Bulk	Hveem	
Oper.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
R. W.	1.99	2.382	38.5	242	1.97	2.402	43	373	1.97	2.406	43	322
R. W.	1.99	2.390	43	252	1.97	2.389	53	388	1.96	2.414	46	394
R. W.	1.98	2.389	41.5	232	1.99	2.389	40.5	316	1.98	2.402	42.5	415
R. W.	1.98	2.389	47	303	1.97	2.396	51	399	1.95	2.408	40	364
R. W.	1.98	2.396	42	266	2.00	2.376	44	337	1.99	2.403	41.5	266
R. W.	1.97	2.395	50.5	264	1.98	2.389	42	355	1.97	2.403	46.5	411
Average Values	1.98	2.390	44	260	1.98	2.390	46	361	1.97	2.406	43	362

	31 psi 30 Gyrations				31 psi 40 Gyrations			
		Bulk	Hveem			Bulk	Hveem	
Oper.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
R. W.	1.97	2.409	44	318	1.96	2.417	39.5	377
R. W.	1.96	2.412	43	385	1.95	2.419	40	378
R. W.	1.98	2.410	43.5	405	1.95	2.408	46	369
R. W.	1.97	2.406	49.5	341	1.95	2.410	39	361
R. W.	1.95	2.416	49.5	338	1.96	2.408	37.5	400
R. W.	1.95	2.413	455	266	1.95	2.418	33	300
Average Values	1.96	2.411	46	342	1.95	2.415	39	364

TABLE 6

Laboratory Results of Modified Molding Procedures THD Type D Hot Mix, River Gravel, Crushed Limestone and Field Sand - Leveling Pressure 1590 psi

	THD Standard				19 psi 30 Gyrations				19 psi 40 Gyrations			
Oper.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
E. H.	1.97	2.400	44	390	1.97	2.385	46	276	1.95	2.399	44	282
E. H.	1.97	2.400	48	315	1.99	2.383	42	201	1.97	2.392	44	279
R. W.	2.00	2.376	45	271	1.99	2.365	36	144	1.95	2.392	42	258
R. W.	2.00	2.371	47	266	2.02	2.342	--	161	1.96	2.390	44	332
W. S.	1.97	2.393	48	306	1.97	2.383	39	194	1.98	2.388	37	233
W. S.	1.98	2.413	49	355	1.95	2.395	44	276	1.96	2.392	41	269
J. M.	2.03	2.335	44	220	1.99	2.379	44	296	1.99	2.383	45	312
J. M.	1.99	2.371	45	223	1.99	2.384	41	262	1.97	2.392	37	366
J. M.	1.99	2.385	47	273	1.99	2.379	43	276	1.98	2.388	42	285
Average Values	1.99	2.383	46	291	1.98	2.377	42	232	1.97	2.391	42	291

	31 psi 30 Gyrations				31 psi 40 gyrations			
Oper.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
E. H.	1.95	2.406	43	310	1.97	2.407	52	427
E. H.	1.94	2.412	42	330	1.97	2.400	44	357
R. W.	1.96	2.397	41	331	1.97	2.408	47	378
R. W.	1.95	2.419	41	318	1.97	2.403	38	403
W. S.	1.96	2.404	39	308	1.95	2.411	45	383
W. S.	1.95	2.397	43	297	1.97	2.405	40	362
J. M.	1.98	2.396	42	398	1.98	2.401	42	407
J. M.	1.98	2.394	39	381	1.96	2.408	42	410
J. M.	1.98	2.397	42	316	1.96	2.405	37	354
Average Values	1.96	2.402	41	339	1.97	2.405	43	387

assumption appears to be reasonable.

The variation in Hveem cohesiometer value is again similar to that reported in the preceding sections. That is, the cohesiometer value increased with compactive effort. It is not known whether the highest energy level used for this material and mix design and group of operators produced a peak value. However, in Table 5 the only significant difference in cohesiometer values in evidence exists for those specimens compacted in accordance with THD molding procedures. Average cohesiometer values measured for the other four levels of compaction energy ranged from 342 to 364 with an over-all average for the four of 358.

Based on average values from Table 6 the Hveem stability presents a different picture. Specimens molded by THD Standard Procedures produced the highest and most consistent values whereas the other specimens molded at different energy levels produced average values that were constant for all practical purposes. The difference in question of about ten percent might be attributed to difference in experience of the operators. All operators had more experience in molding by THD Standard Procedures. It is also reasonable to expect that excessive gyrations may have changed the surface texture and particle shape sufficiently to change the internal friction. This would be particularly true if the crusher fines exercised a controlling factor on the internal friction. This material was softer than the other materials in the mix and was therefore more vulnerable to degradation and too it was the only highly textured material in the blend.

PHASE IV

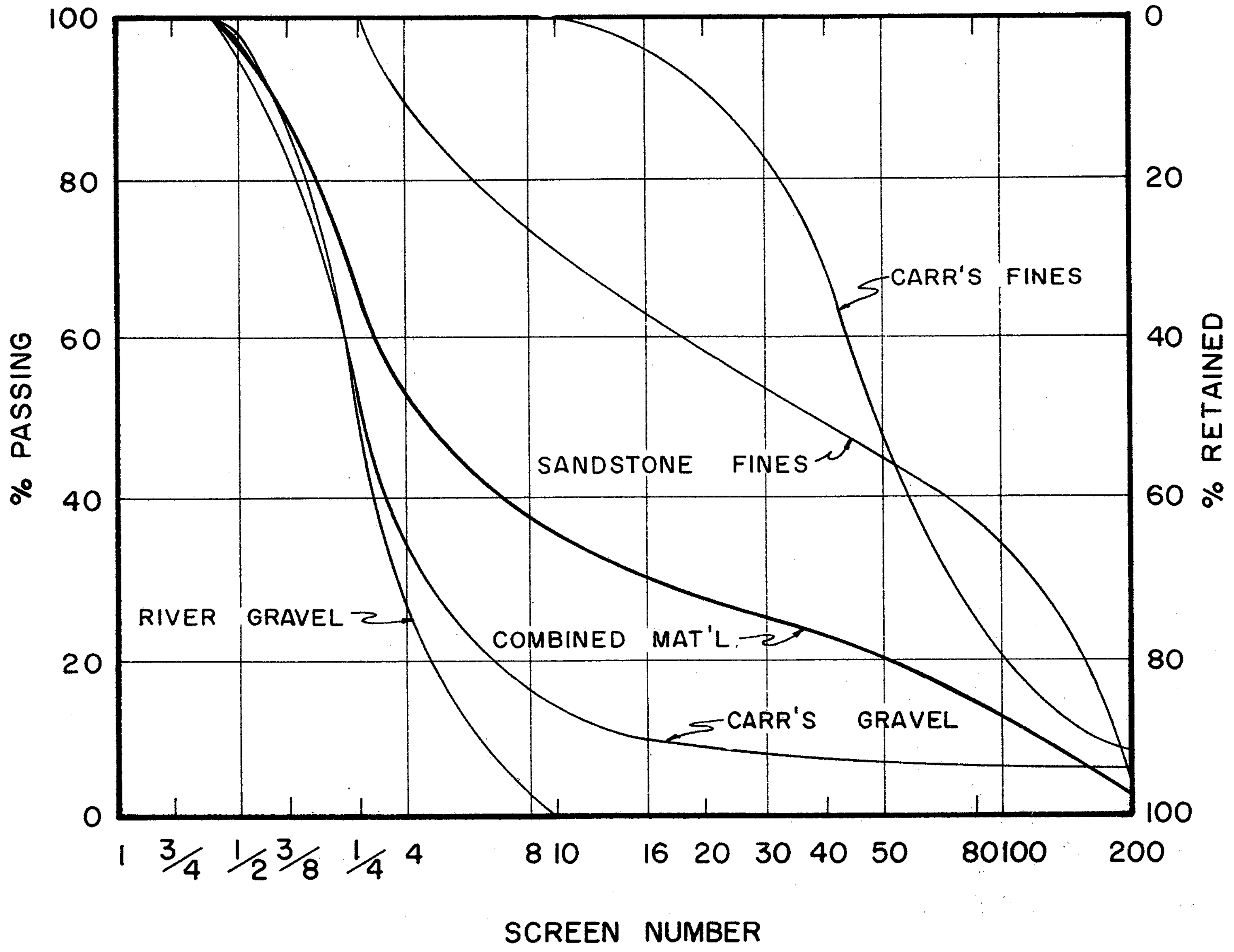
Materials

The gradings of the materials used in Phase IV of this study are shown in Figure 5. These materials were blended to form the combination shown in Figure 5 by the heavy line on this plot. Reference to Table 7 will show the reader that these are materials of average characteristics with the possible exception of the Varisco (sandstone) screenings. This material has a low density, high absorption, and high Los Angeles abrasion loss. From the data shown in Table 7 it would appear that the mix would tolerate more asphalt cement than the selected 5 percent. In the practical use of hot-mix asphaltic concrete for overlays on fairly rigid pavements many engineers favor lower asphalt content to doubly insure against the possibility of plastic instability. This objective has often been accomplished at the expense of durability. Evidence of this was nationwide just a few years ago. Reports from widely separated areas indicated early failure of pavements by water susceptibility and/or raveling. To minimize these early failures from the causes mentioned aggregates were more thoroughly cleaned or the asphalt content was increased. In special cases the aggregates were cleaned and treated with a surfactant such as hydrated lime to improve adhesion and insure water resistance. At the time the material under discussion was used (1960) it was thought that it would be of limited durability. At the time of this writing (1963) this light traffic pavement has been in service for about 2-1/2 years. Considerable distress was in evidence about one year ago. The entire section is now under contract for rebuilding.

Variable Compaction Energy for Different Operators

Shown in Tables 8 and 9 are laboratory data on the asphalt aggregate mixture described in Figure 5 and Table 7. Four different operators were used in this phase of the study, and five different levels of compaction energy were involved. The operator reproducibility was better than for previous materials used in the over-all study, if bulk density of the specimens is the basis of comparison.

Apparently the compaction modification represented by 40 gyrations at 19 psi foot pressure and a leveling pressure of 1590 psi was essentially equivalent to THD Standard. It is again evident from the data that the cohesiometer value is improved to a point for a mix of this type when the compaction energy is increased. Beyond a certain point in the compaction process this value may decrease; however it is not known from the data exactly where the decrease will occur. It would be interesting, and per-


100
80
60
40
20
0
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20
40
60
80
100
% PASSING
% RETAINED
CARR'S FINES
SANDSTONE FINES
RIVER GRAVEL
COMBINED MAT'L.
CARR'S GRAVEL
1
3/4
1/2
3/8
1/4
4
8
10
16
20
30
40
50
80
100
200
SCREEN NUMBER

FIGURE 5

TABLE 7

Design Values for Mix FM 1774

Aggregate	Specific Gravity
30.0% Gifford-Hill Gravel	2.607
35.0% Carr's Coarse Gravel	2.493
19.0% Carr's Fine Gravel	2.610
16.0% Varisco Screenings	2/181
85-100 Penetration Asphalt	0.990

Asphalt Content, %	Hveem Stability, %	Voids, %
4.0	37	8.5
4.7	37	6.5
5.4	35	4.0
6.1	36	2.5
6.8	25	1.0

Theoretical Specific Gravity

$$\text{Aggregate, } G = \frac{100}{\frac{30}{2.607} + \frac{35}{2.493} + \frac{19}{2.610} + \frac{16}{2.181}} = 2.489$$

$$\text{Mix, } G_T = \frac{100}{\frac{95}{Y} + \frac{5}{0.990}} = 2.313$$

TABLE 8

Laboratory Results of Modified Molding Procedures
THD Type D Hot-Mix From FM 1774 Using River Gravel,
Coarse and Fine Sand and Field Sand

	THD Standard					19 psi 30 Gyrations					19 psi 40 Gyrations			
Oper.	Height	Sp. Gr.	Stab.	Coh.	Oper.	Height	Sp. Gr.	Stab.	Coh.	Oper.	Height	Sp. Gr.	Stab.	Coh.
WS	2.03	2.294	37	150	RW	2.04	2.291	46	142	WS	2.03	2.286	48	117
WS	2.03	2.291	41	172	RW	2.04	2.290	46	155	RW	2.05	2.281	41	126
WS	2.04	2.280	42	165	RW	2.04	2.274	46	136	EH	2.04	2.280	45	129
WS	2.04	2.279	43	155	RW	2.05	2.280	43	157	EH	2.05	2.277	42	138
WS	2.03	2.281	43	165	RW	2.05	2.277	45	120	EH	2.04	2.285	46	164
WS	2.04	2.284	37	148	RW	2.05	2.268	45	160	EH	2.04	2.294	40	145
Average Values	2.03	2.285	41	159		2.04	2.280	45	145		2.04	2.284	44	137

	31 psi 30 Gyrations					31 psi 40 Gyrations			
Oper.	Height	Sp. Gr.	Stab.	Coh.	Oper.	Height	Sp. Gr.	Stab.	Coh.
WS	2.02	2.292	48	294	WS	2.02	2.310	44	197
EH	2.03	2.309	42	274	EH	2.02	2.308	41	235
WS	2.02	2.303	46	244	WS	2.02	2.304	42	183
EH	2.03	2.306	45	273	EH	2.02	2.309	39	212
WS	2.03	2.301	43	256	RW	2.01	2.302	45	215
EH	2.02	2.308	42	281	RW	2.03	2.299	42	244
Average Values	2.02	2.303	44	270		2.02	2.305	42	214

TABLE 9

Laboratory Results of Modified Molding Procedures THD Type D Hot-Mix From FM 1774 Using River Gravel Coarse and Fine Sand and Field Sand Constant Leveling Pressure of 1590 psi

	THD Standard				19 psi 30 Gyrations				19 psi 40 Gyrations			
Oper.	Height	Sp. Gr.	Stab	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
R. W.	2.04	2.292	42	206	2.05	2.269	43	145	2.05	2.268	38	124
R. W.	2.03	2.292	44	201	2.05	2.271	43	197	2.03	2.282	45	172
R. W.	2.06	2.266	45	133	2.03	2.282	43	143	2.03	2.285	48	156
R. W.	2.06	2.274	48	165	2.05	2.268	44	144	2.01	2.301	49	163
R. W.	2.05	2.301	47	248	2.03	2.276	47	164	2.03	2.286	45	158
R. W.	2.02	2.294	46	226	2.09	2.257	46	160	2.05	2.289	43	147
J. M.	2.04	2.254	44	167	2.04	2.266	44	173	2.03	2.272	46	181
J. M.	2.04	2.258	42	186	2.04	2.262	44	146	2.03	2.272	43	191
J. M.	2.04	2.259	44	211	2.05	2.263	45	169	2.03	2.270	46	209
Average Values	2.04	2.277	44	194	2.05	2.268	44	160	2.03	2.281	45	166

	31 psi 30 Gyrations				31 psi 40 Gyrations			
Oper.	Height	Sp. Gr.	Stab	Coh.	Height	Sp. Gr.	Stab.	Coh.
R. W.	2.02	2.304	45	122	2.00	2.289	46	191
R. W.	2.03	2.292	44	269	2.02	2.296	45	222
R. W.	2.01	2.299	47	211	1.98	2.311	49	273
R. W.	2.03	2.295	42	177	2.01	2.292	39	248
R. W.	2.06	2.293	40	209	2.00	2.302	43	238
R. W.	2.07	2.291	39	281	2.00	2.305	46	369
J. M.	2.02	2.280	46	240	2.03	2.284	46	246
J. M.	2.03	2.273	45	195	2.03	2.285	44	240
J. M.	2.03	2.281	46	182	2.04	2.285	48	230
Average Values	2.03	2.289	44	209	2.01	2.294	45	250

haps quite valuable, to know when this peak value is reached in service. It is reasonable to expect that there is a general improvement (increase) in the tensile strength value of such a material for a period of years. It is an established fact that the cohesiometer value varies directly with asphalt viscosity and these data appear to clearly indicate an increase in cohesion with added compactive effort, at least to a certain point. In service with the passing of time, both of the factors are at work to improve the bending strength of asphaltic concrete. It must be remembered that there are several other factors to be considered in the over-all problem of pavement distress and temperature is definitely not the least of these. Such other factors as rate of loading, tire contact area, magnitude of strain or deflection and repetitions of load cannot be overlooked.

The data in Table 8 indicate that the Hveem stability for this mix is essentially unaffected by differences in compactive effort, density or operator technique. The reader might conclude that there was not sufficient variation in the compactive effort and this may well be true for a mix of this type but it is estimated that the highest effort applied to this mix was more than double the least effort. What then may be concluded from this? If to no one else, this information would be of value to the contractor who might be operating on a specification requiring field cores of certain density and/or Hveem stability. Also of possible interest to the contractor who might operate on a required Marshall stability measured on laboratory specimens is the fact that Marshall stability and Hveem cohesion correlate reasonably well. The variation is direct within about plus or minus fifteen percent for most mixes. This would mean that Marshal stability values might be increased 25 to 50% by simply increasing compactive effort. This, of course, assumes a mix similar to the one in question.

Phase V

Materials

The materials used in Phase V of the study are described in Figure 6 and Table 10. From the grading curve of the combined material shown in Figure 6 it is evident that the aggregate combination has produced what is often referred to as a gap or skip graded mixture. Approximately five percent of material is between the No. 10 and No. 40 sieves. This type mix is not particularly unusual in Texas and is entirely within grading specifications. Some agencies design skip graded mixes to serve specific purposes. Service records in Texas indicate that such mixes perform satisfactorily under normal circumstances.

Since mixes such as this are used in other areas as well as Texas, it was included in the modified compaction study. From the data in Table 10 it would appear that the mix stability is only slightly sensitive to changes in asphalt content. The data on final voids as a function of asphalt content do not follow the normal pattern. When the asphalt content was changed from 4.0 to 4.5 percent there was a two percent change in voids whereas the same change in asphalt content from 5.5 to 6.0 caused only one-half percent change in voids. When the total voids of a mix are reduced to less than one percent, it is generally expected that the voids-versus-asphalt content would deviate from a straight line. A plot of these data reveals a deviation at about three percent voids. These are dense low absorption aggregates so very little correction should be allowed for this factor. The writers have no explanation to offer for this deviation if it is assumed that the data presented are completely reliable.

Variable Compaction Energy for Different Operators

In Phase V the number of different operators was reduced to two and the leveling pressure was held constant at 1590 psi while five different levels of compaction energy were used. The results of these tests are included in Tables 11 through 15.

An examination of the bulk density data reveals higher densities for operator R. W. throughout the series of tests, if the values in Table 11 are excluded. The difference in the average value of 0.001 is, however, not considered significant. What is indeed significant in the density data of Table 11 is the operator repeatability and the reproducibility between operators. No density value listed varied more than ± 0.01. This is a tribute not only to the operator but also to the THD method of compaction. The method dictates the end point of compaction and the specific end point is

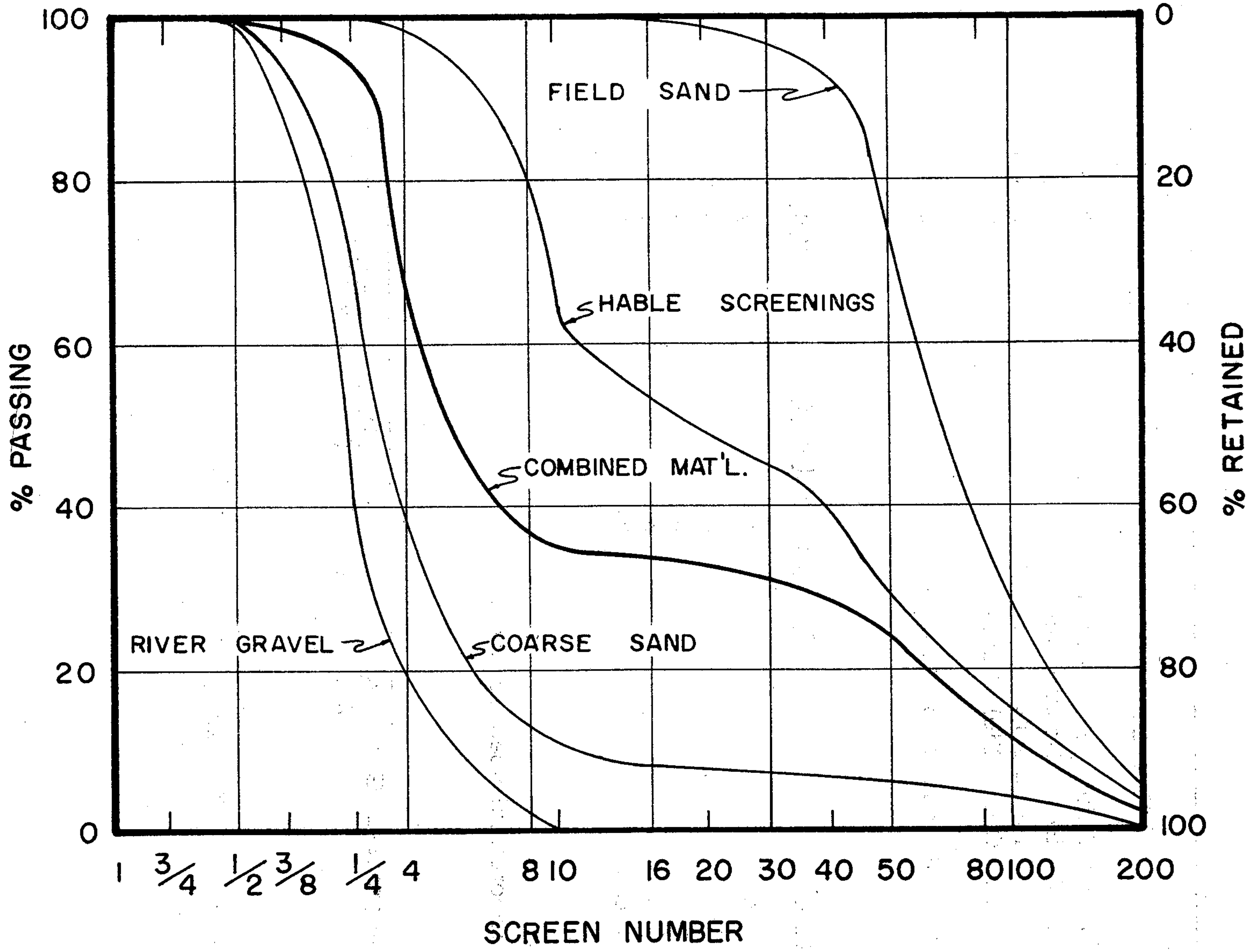

100
80
60
40
20
0
% PASSING
0
20
40
60
80
100
% RETAINED
FIELD SAND
HABLE SCREENINGS
COMBINED MAT'L.
RIVER GRAVEL
COARSE SAND
1
3/4
1/2
3/8
1/4
4
8
10
16
20
30
40
50
80
100
200
SCREEN NUMBER

FIGURE 6

TABLE 10

Design Values for Mix From Centerville

Aggregates	Specific Gravity
46.0% Gifford-Hill Gravel	2.607
15.0% Hable Coarse Sand	2.650
14.0% Hable Screenings	2.661
25.0% Carter Field Sand	2.635
85-100 Penetration Asphalt	0.990

Asphalt, %	Hveem Stability, %	Voids, %
4.0	37	7.5
4.5	36	5.5
5.0	35	3.3
5.5	35	1.8
6.0	32	1.2

Theoretical Specific Gravity

$$\text{Aggregate, } G = \frac{100}{\frac{46}{2.607} + \frac{15}{2.650} + \frac{14}{2.661} + \frac{25}{2.635}} = 2.627$$

$$\text{Mix, } G_T = \frac{100}{\frac{95.3}{Y} + \frac{4.7}{0.990}} = 2.437$$

TABLE 11

THD Type D Hot-Mix River Gravel, East Texas Stone and Field Sand Molded by THD Standard Procedure - Leveling Pressure 1590 psi

	OPERATOR C. W.				OPERATOR R. W.			
Sample No.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.
1	1.97	2.354	39	93	1.99	2.339	43	80
2	1.98	2.334	37	51	1.98	2.358	40	104
3	1.98	2.351	41	77	1.99	2.350	44	83
4	2.00	2.338	42	88	1.99	2.338	39	73
5	2.00	2.345	43	64	2.00	2.334	38	79
6	2.01	2.331	40	60	2.00	2.336	33	92
Average Values	1.99	2.343	40	72	1.99	2.342	40	85

TABLE 12

THD Type D Hot-Mix River Gravel, East Texas Stone and Field Sand Molded at 19 psi Foot Pressure 30 Gyrations - Leveling Pressure 1590 psi

	OPERATOR C. W.				OPERATOR R. W.			
Sample No.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.
1	1.99	2.338	40	84	2.00	2.344	42	87
2	1.99	2.341	37	79	1.99	2.349	41	78
3	1.99	2.343	41	93	2.00	2.354	43	86
4	1.98	2.345	38	112	1.99	2.357	43	79
5	1.99	2.341	38	110	1.98	2.351	40	90
6	1.99	2.338	41	98	1.99	2.348	41	105
Average Values	1.99	2.342	39	96	1.99	2.351	42	88

TABLE 13

THD Type D Hot-Mix River Gravel, East Texas Stone and
Field Sand - Molded at 19 psi Foot pressure, 40 gyrations
Leveling Pressure 1590 psi

	OPERATOR C. W.				OPERATOR R. W.			
Sample No.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.
1	1.98	2.340	39	97	1.97	2.353	36	87
2	1.99	2.342	34	97	1.98	2.354	39	88
3	2.00	2.343	39	81	1.98	2.354	38	87
4	1.98	2.345	38	93	1.98	2.351	47	96
5	2.00	2.343	40	97	1.99	2.347	35	76
6	1.98	2.347	39	91	1.99	2.351	39	80
Average Values	1.99	2.343	38	94	1.98	2.352	39	86

TABLE 14

THD Type D Hot-Mix River Gravel, East Texas Stone and Field Sand
Molded at 31 psi Foot Pressure 30 Gyrations - Leveling Pressure 1590 psi

	OPERATOR C. W.				OPERATOR R. W.			
Sample No.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.
1	1.97	2.349	40	116	2.00	2.363	46	121
2	1.98	2.346	40	93	2.01	2.355	43	129
3	1.97	2.353	41	118	2.00	2.358	42	129
4	1.98	2.345	36	110	1.99	2.355	41	101
5	1.99	2.351	42	105	1.99	2.353	45	126
6	1.98	2.355	39	113	1.99	2.359	43	124
Average Values	1.98	2.350	40	109	2.00	2.357	43	122

TABLE 15

THD Type D Hot-Mix River Gravel, East Texas Stone and Field Sand Molded at 31 psi Foot Pressure, 40 Gyrations- Leveling Load 1590 psi

	OPERATOR C. W.				OPERATOR R. W.			
Sample No.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.	Height	Bulk Sp. Gr.	Hveem Stab.	Hveem Coh.
1	1.97	2.367	41	99	2.03	2.347	35	109
2	1.98	2.355	39	123	1.99	2.365	41	117
3	1.97	2.369	41	134	2.03	2.364	43	118
4	1.97	2.360	38	138	1.97	2.370	42	110
5	1.98	2.360	39	117	1.97	2.367	43	116
6	1.97	2.360	37	100	1.98	2.363	40	88
Average Values	1.97	2.362	39	119	1.99	2.363	41	111

dependent upon the type and grading of the aggregate and the asphalt content.

As may be noted from the five tables the grand average of the stability is 40.1 with a range of 38 to 43 for both operators and all five energy levels. The THD method produced averages of 40 for both operators. Although the energy input to the specimens in Table 15 is threefold or more than that for the specimens in Table 11, the average stability for the two operators is 40. Again this would seem to indicate that certain materials of fixed grading have a limiting Hveem stability, provided the asphalt content is also fixed. This same conclusions cannot be drawn when one considers the Hveem cohesiometer value.

Referring again to the data in this group of tables one may observe the change in cohesiometer values with higher energies of compaction. The Hveem cohesion appears to peak for this design and mix at 31 psi constant foot pressure and 30 to 40 gyrations. The data are not sufficient to accurately define this peak just as was the case in the previous phases of this study; however, a review of previous data shown will indicate that most of the mixes present patterns of cohesiometer values that are very much alike. The patterns are such that it is reasonably safe to say that for given materials and design there are separate and distinct levels of compaction energies producing maximum Hveem stability in one case and maximum Hveem cohesion in the other. Apparently it requires, for certain mixes, more than twice the compaction energy to produce peak values of cohesion than it does for maximum Hveem stability. It is possible that with increasing compaction energy that fines are produced at the asphalt-aggregate interface and these fines produce an asphalt-filler mastic of higher viscosity and higher viscosity is revealed as a higher cohesiometer value. When the "manufactured" filler content exceeds a certain value for mixes of fixed asphalt content the aggregates may be so degraded that adhesion is reduced and hence there results a lower cohesiometer value. Hveem cohesion, it must be remembered, is strongly influenced by the viscosity of the asphaltic binder.

Phase VI

Materials

The materials described in Figure 7 and Table 16 are typical of certain areas of East Texas and are also to be found in other areas of the United States. It is evident from Figure 7 that the aggregate blend is formed from two fractions of iron ore produced from the same pit by crushing and screening operations. The combined material produced a fairly dense grading; however, for an idealized grading that falls within THD specifications, the blend is on the coarse side. In the fines end of the grading curve median values are closely approached.

From Table 16 it is to be noted that the relationship between asphalt content and voids in the compacted specimen is linear. These data on stability, cohesion and voids like that in previous similar tables represent THD district laboratory designs. The test specimens were prepared following standard THD test methods. Each value listed represents an average of three or more measurements.

It is interesting to note that the Hveem cohesiometer value increases quite rapidly when the asphalt content is changed from 5.5 to 6.0 percent. When the listed cohesiometer values are plotted against asphalt content an interpolated value of 80 is revealed for the job mix formula. More will be said about this in the section to follow.

Variable Compaction Energy for Different Operators

Tables 17 through 21 include laboratory test data on THD Type D hot-mix made from a single source material commonly referred to as iron ore gravel. The data are arranged in much the same way as those presented in Phase V of this study. A total of three different operators was used; however, Operator J.M. was purposely restricted to only half the number of specimens. A study of all the density data included in these five tables indicates good operator repeatability with only slightly poorer reproducibility from operator to operator.

From the average specific gravities listed a range from 2.555 to 2.591 is evident with an over-all average of 2.572. Operator J.M. consistently produced specimens of lower density than did either of the other operators; whereas, this same operator produced specimens with Hveem stabilities ranging from 10 to 25 percent higher than those for the other two operators

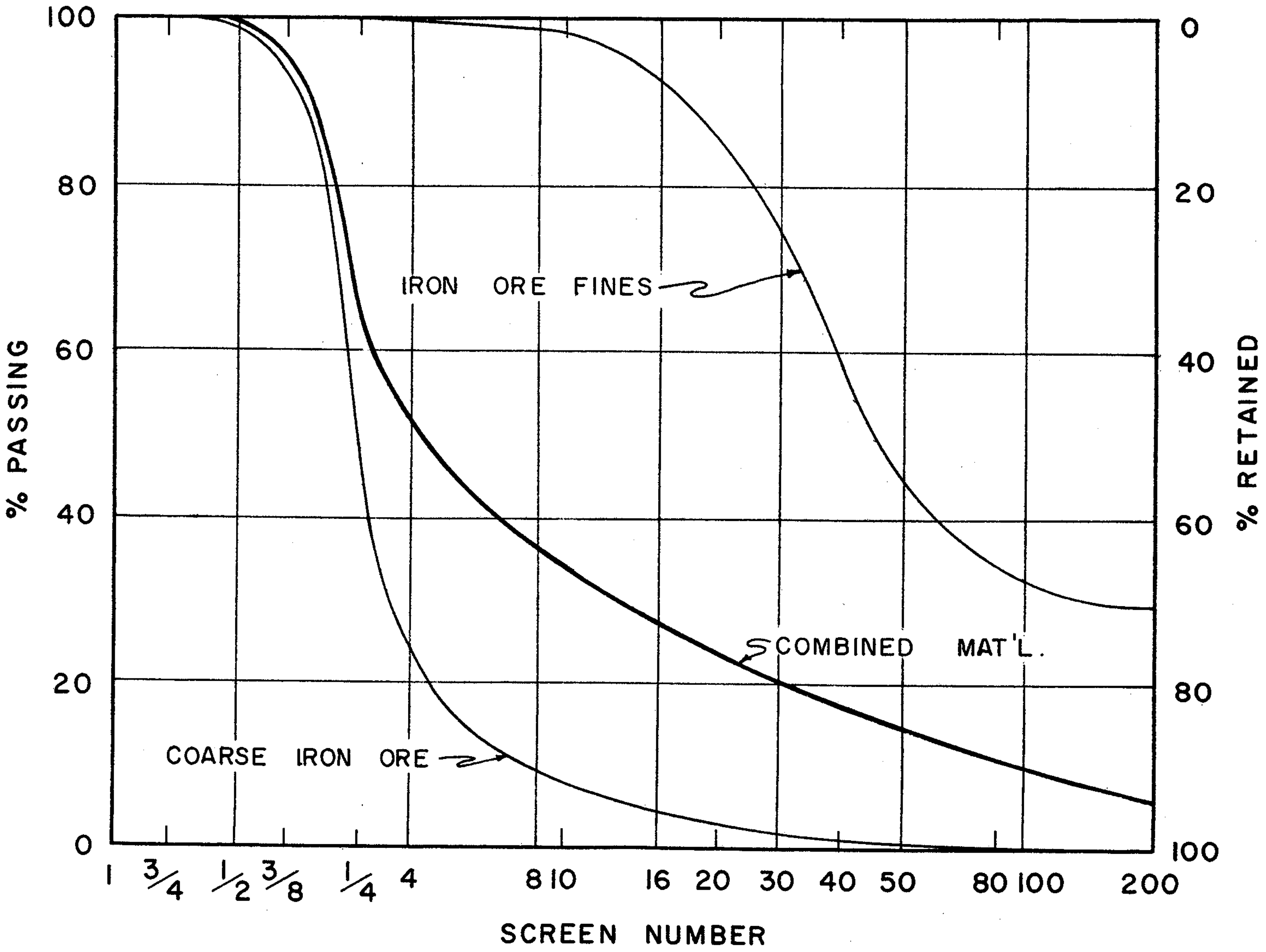

100
80
60
40
20
0
% PASSING
0
20
40
60
80
100
% RETAINED
IRON ORE FINES
COMBINED MAT'L.
COARSE IRON ORE
1
3/4
1/2
3/8
1/4
4
8
10
16
20
30
40
50
80
100
200
SCREEN NUMBER

FIGURE 7

TABLE 16

Design Values for Mix From Fairfield

Aggregate	Specific Gravity
66.0% Gilpin Iron Ore (+ No. 10)	2.875
34.0% Gilpin Iron Ore (- No. 10)	2.767
85 - 100 Penetration Asphalt	0.990

Asphalt, %	Hveem Stability, %	Hveem Cohesion	Voids, %
4.0	48	38	8.5
4.5	42	52	6.6
5.0	46	74	5.4
5.5	40	95	4.4
6.0	41	154	2.2

Theoretical Specific Gravity

$$\text{Aggregate, } G = \frac{100}{\frac{66}{2.875} + \frac{34}{2.767}} = 2.854$$

$$\text{Mix, } G_T = \frac{100}{\frac{94.8}{Y} + \frac{5.2}{0.990}} = 2.599$$

TABLE 17

THD Type D Hot-Mix Iron Ore Gravel and Screenings - THD Standard Molding Procedure Leveling Pressure 1590 psi

Sample	OPERATOR C. W.				OPERATOR R. W.				OPERATOR J. M.			
		Bulk	Hveem			Bulk	Hveem			Bulk	Hveem	
No.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
1	2.00	2.547	42	205	1.97	2.567	43	380	2.00	2.554	42	281
2	2.04	2.555	45	235	1.97	2.570	41	314	2.00	2.561	44	348
3	2.01	2.584	42	247	1.97	2.588	36	365	2.02	2.552	44	344
4	1.99	2.582	41	320	1.97	2.577	37	426	----	------	--	---
5	1.98	2.596	43	342	1.97	2.586	41	454	----	------	--	---
6	2.02	2.558	41	311	1.96	2.580	46	377	----	------	--	---
Average Values	2.01	2.570	42	277	1.97	2.576	41	366	2.01	2.555	43	324

TABLE 18

THD Type D Hot-Mix Iron Ore Gravel and Screenings Molded at 30 psi Foot Pressure 30 Gyrations Leveling Pressure 1590 psi

Sample	OPERATOR C. W.				OPERATOR R. W.				OPERATOR J. M.			
		Bulk	Hveem			Bulk	Hveem			Bulk	Hveem	
No.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
1	1.99	2.560	38	288	1.97	2.555	42	262	1.99	2.571	49	332
2	1.98	2.576	39	372	1.97	2.569	42	361	2.01	2.553	51	279
3	1.97	2.582	37	---	1.97	2.557	45	302	1.99	2.565	52	280
4	1.99	2.556	40	248	1.99	2.549	44	370	----	-----	--	---
5	2.00	2.562	37	229	1.97	2.576	46	270	----	-----	--	---
6	1.99	2.575	37	304	1.98	2.556	47	324	----	------	--	---
Average Values	1.99	2.568	38	288	1.97	2.560	44	315	2.00	2.563	51	297

TABLE 19

THD Type D Hot-Mix Iron Ore Gravel and Screenings
Molded at 30 psi Foot Pressure and 40 Gyrations
Leveling Pressure 1590 psi

Sample	OPERATOR C. W.				OPERATOR R. W.				OPERATOR J. M.			
		Bulk	Hveem			Bulk	Hveem			Bulk	Hveem	
No.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
1	1.98	2.574	44	351	1.97	2.577	40	216	1.99	2.571	49	332
2	1.99	2.574	37	311	1.97	2.563	42	331	2.01	2.553	51	279
3	1.98	2.574	40	307	1.97	2.573	43	325	1.99	2.565	52	280
4	1.98	2.570	35	382	1.97	2.575	30	345	----	------	--	---
5	1.99	2.569	39	202	1.97	2.580	43	317	----	------	--	---
6	1.98	2.578	37	341	1.98	2.572	42	311	----	------	--	---
Average Values	1.98	2.573	39	316	1.97	2.575	42	307	2.00	2.563	51	297

TABLE 20

THD Type D Hot-Mix Iron Ore Gravel and Screenings
Molded at 50 psi Foot Pressure and 30 Gyrations
Leveling Pressure 1590 psi

Sample	OPERATOR C. W.				OPERATOR R. W.				OPERATOR J. M.			
		Bulk	Hveem			Bulk	Hveem			Bulk	Hveem	
No.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Con.
1	1.97	2.593	44	354	1.96	2.577	43	444	2.00	2.566	49	287
2	1.96	2.595	46	288	1.96	2.573	43	377	1.98	2.562	50	335
3	1.98	2.578	42	256	----	------	--	---	1.98	2.565	42	252
4	1.99	2.574	38	292	1.98	2.577	42	348	----	------	--	---
5	1.98	2.591	44	178	1.93	2.584	44	284	----	------	--	---
6	1.98	2.584	46	241	1.97	2.582	44	342	----	------	--	---
Average Values	1.98	2.586	43	268	1.96	2.579	43	359	1.99	2.564	47	291

TABLE 21

THD Type D Hot-Mix Iron Ore Gravel and Screenings Molded at 50 psi Foot Pressure and 40 Gyrations Leveling Pressure 1590 psi

	Operator C. W.				Operator R. W.				Operator J. M.			
		Bulk	Hveem			Bulk	Hveem			Bulk	Hveem	
Sample No.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.	Height	Sp. Gr.	Stab.	Coh.
1	1.97	2.588	44	267	1.98	2.582	41	309	2.01	2.567	49	394
2	1.98	2.606	33	267	1.98	2.580	45	419	1.98	2.582	50	347
3	1.96	2.584	41	196	2.00	2.568	41	344	1.99	2.582	46	348
4	1.97	2.591	43	261	2.00	2.585	44	337	----	-----	--	---
5	1.97	2.591	41	173	1.96	2.599	39	407	----	-----	--	---
6	1.98	2.586	38	186	1.98	2.579	46	279	----	-----	--	---
Average Values	1.97	2.591	40	225	1.98	2.582	43	349	1.99	2.577	48	363

except for specimens molded by THD standard procedure.

A review of all factors that might possibly explain these stability differences is then in order. As has been stated previously all operators in a series of tests such as these were instructed to follow the same procedure when operating at a selected compaction energy level. This does not, however, give assurance that the energy input will be precisely the same among operators. Operator J.M. did not have the strength or stamina of the other operators and this was taken into consideration when he was selected to prepare three instread of six specimens at each energy level. Nevertheless, based on results of density and stability it must be concluded that Operator J.M. actually put less energy into the specimens he molded. The higher stability values might again be attributed to less intraparticle attrition in mixes supposedly compacted at equal energy levels.

If the cohesiometer value pattern for this mix is similar to those patterns of previous mixes, then it would be expected (based on previously expressed explanations) that peak values of cohesion would occur later in the series of increasing compaction energies for Operator J.M. than for the other operators.

Again the reader is cautioned to disregard the series of specimens molded by THD standard procedures when comparing the data obtained at different levels of compaction energy. Then does the cohesiometer value peak later in the compaction series for Operator J.M? It does, indeed! Operator C.W. reached a peak in cohesion at the second level as shown in Table 19. Operator R.W. reached a high value in level three and Operator J.M. had the highest average cohesiometer value at the fourth and highest level of compaction energy.

The general patterns described have occured in the several different phases of this study, but it is pointed out again that several factors play a part in magnitude and location of the cohesion peak value in the individual test series.

Phase VII

Introduction

In almost any research plan there are certain points of weakness and these weaknesses may or may not have an important effect on the results of the experiments. In the present study some question was raised concerning certain aspects of the Hveem stability testing procedure as outlined by the Texas Highway Department.

A number of agencies use the Hveem method for evaluating the stability of asphalt-aggregate mixtures. A majority of these agencies use the procedure as outlined by Test Method No. Calif. 304-C. The Texas Highway Department, on the other hand, uses a modification of this procedure for which the details are given in Test Method Tex-208-F. Two major differences exist between the two methods, namely, initial displacement and height of specimen. The California method calls for a 2.50-inch (idealized) high specimen; whereas, the Texas method calls for a 2.00-inch high specimen. Both procedures give height adjustment charts so this factor is not critical. Initial displacement for the California method is 0.200 of an inch as opposed to 0.075 of an inch for Texas. Both methods allow a tolerance, ± 0.005 of an inch for Texas and ± 0.050 of an inch for California.

It may also be noted from reading the two procedures that there is no difference in the amount a specimen is engaged in the upper steel ring of the testing device. Texas' method calls for 3/16-inch for all specimens which must also be 2.00 ± 0.06 inches in height.

Questions concerning the effect on stability of this factor were investigated to a limited extent for a given mix and the data are listed in Table 20.

Materials

Shown in Figure 8 is a typical grading curve for a mixture of wet bottom boiler slag and crushed limestone fines. For comparison purposes Fuller's density curve is also shown for the same top size aggregate. Extensive research has been carried out in the Institute's Laboratory with mixtures of this slag and other aggregates so the characteristics of this and similar blends are well known. It will be evident why this material was chosen for this phase of the program as the data are presented.

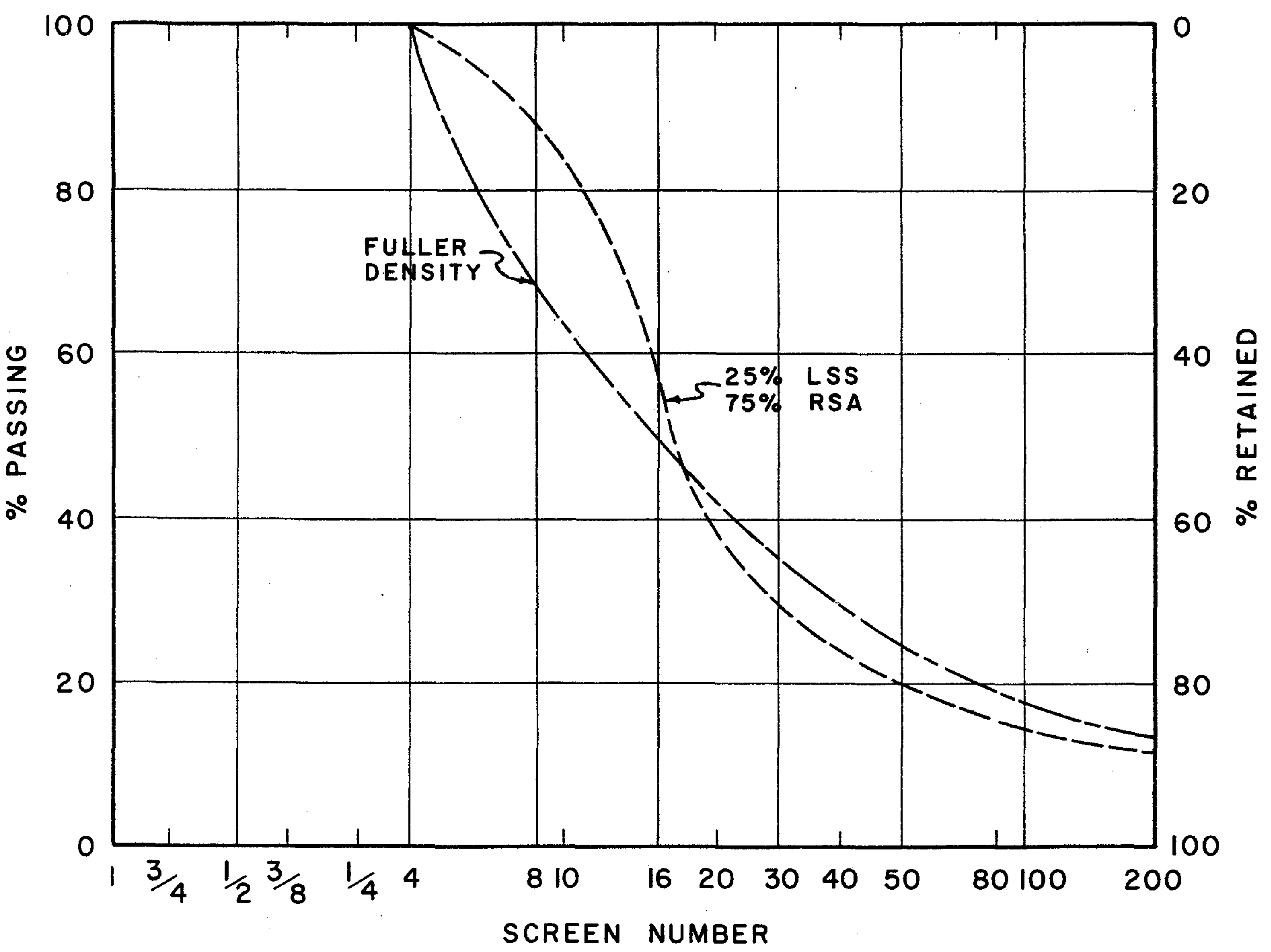

100
80
60
40
20
0
% PASSING
0
20
40
60
80
100
% RETAINED
FULLER DENSITY
25% LSS
75% RSA
1
3/4
1/2
3/8
1/4
4
8
10
16
20
30
40
50
80
100
200
SCREEN NUMBER

FIGURE 8

Hveem Stability Vs. Effective Specimen Height and Top Ring Engagement

In Table 22 are data taken on fifteen specimens of identical design. The first six specimens are of essentially the same density and all were engaged in the top ring of the stabilometer 0.19 of an inch. Exposure to the liquid phase of the stabilometer varied from 1.72 to 1.80 inches. No trend in the stability value was revealed. Three additional specimens of higher density were also tested in the same manner. The data show somewhat higher stability values but this increase can be attributed to the increased density.

The next six specimens were tested with a fixed amount of exposure to the diaphragm of the stability apparatus and the top ring engagement was varied from 0.11 to 0.24 of an inch. As may be noted from the limited data no trend is indicated.

The Texas and California methods fix the amount of top ring engagement but the Texas method allows ± 0.06 of an inch tolerance in the over-all height of the test specimen. From the previous data presented in Phases I through VI of this study it appears that variation in stability caused by differences in compaction obtained by different operators using the same method of densification are of much greater concern.

Whether the specimen is engaged 0.10 or 0.19 of an inch in the top ring is of minor consequence and quite possibly the difference cannot be detected by the usual methods of measurement.

In this experiment a fine graded mix was used. The top size of the aggregate was 100 percent passing the No. 4 sieve. It was considered necessary to use a small top size aggregate so the effect of this aspect of the mix would be minimized or eliminated. Normally larger top size aggregate is used and had this been the case for the study under discussion, still less change would have been expected.

TABLE 22

Effect of Amount of Top Ring Engagement and Diaphragm Exposure on Hveem Stability Values

Sample No.	Bulk Sp.Gr.	Total Percent Voids	Sample Height, In.	Ring Engaged, In.	Diaphragm Exposed, In.	Hveem Stability
1	2.297	6.3	1.94	0.19	1.75	30
2	2.281	6.8	1.93	0.19	1.74	31
3	2.313	5.5	1.91	0.19	1.72	30
4	2.298	6.3	1.99	0.19	1.80	36
5	2.324	4.8	1.99	0.19	1.80	32
6	2.322	5.0	1.98	0.19	1.79	30
7	2.386	2.5	2.06	0.19	1.87	34
8	2.406	1.9	2.04	0.19	1.85	36
9	2.392	2.4	2.06	0.19	1.87	38
10	2.300	6.0	1.92	0.11	1.81	39
11	2.296	6.2	1.93	0.12	1.81	33
12	2.290	6.4	1.93	0.12	1.81	35
13	2.299	6.1	2.04	0.23	1.81	42
14	2.415	1.7	2.05	0.24	1.81	32
15	2.370	3.2	2.05	0.24	1.81	36

Note: All test specimens molded by Texas Highway Department Test Method Tex-208 F. Mixture 75% RSA, 25% LSS, 7% OA-90. (See Figure 8). Mixed at temperature equivalent to viscosity of 100 SSF of asphalt used. Molded at 250°F.

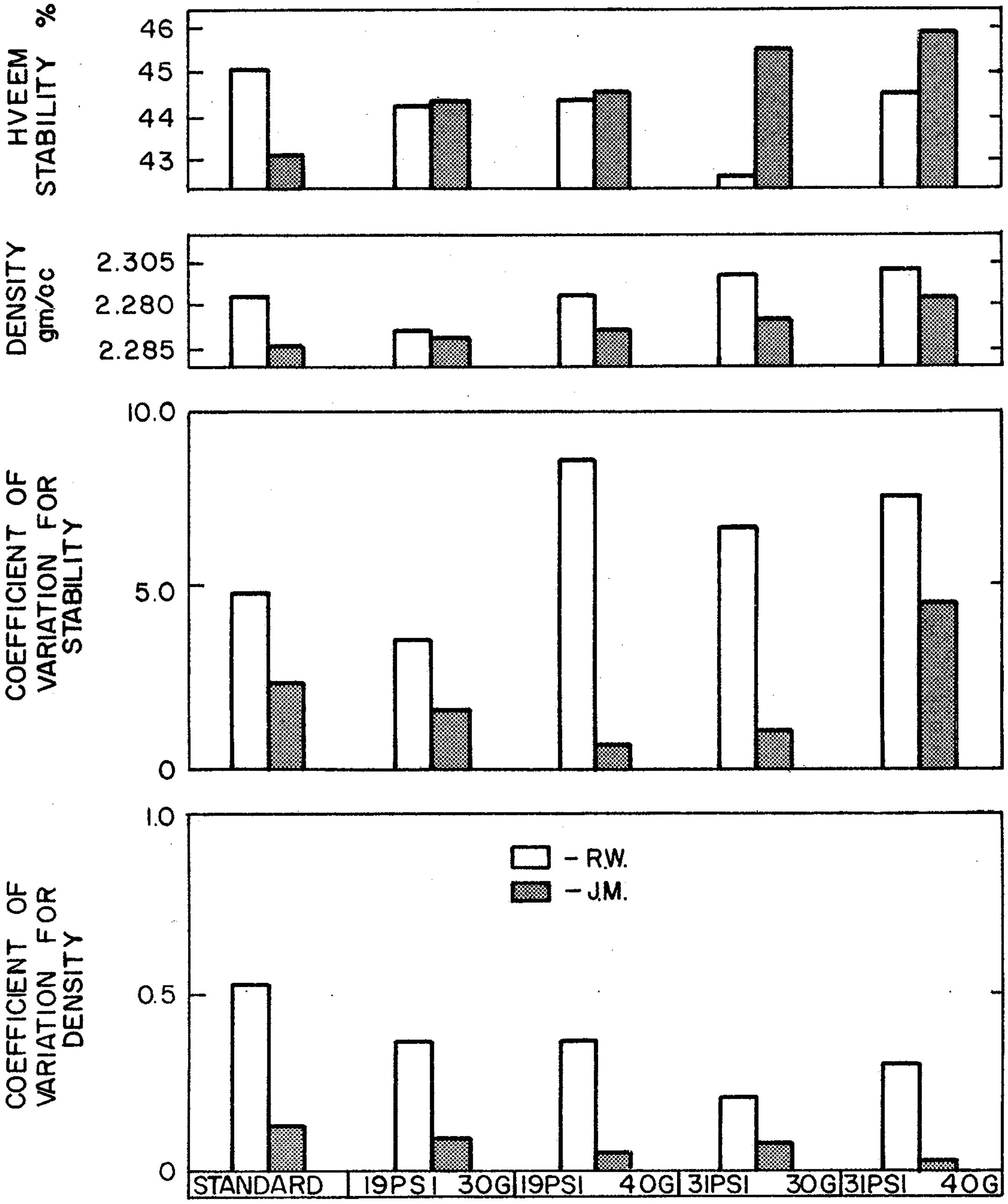
PHASE VIII

A limited statistical study was performed on some of the data discussed in previous phases to determine the extent of variations in density and Hveem stability resulting from the various compactive efforts utilized. The results of these computations are presented in Table 23 in terms of standard deviation, S, and coefficient of variation, C.V., expressed as a percentage. The standard deviation indicates that in a normal distribution of events or density values as in this case, 67 percent of the number of values will be with the range set by the mean value plus or minus the standard deviation. Since the standard deviation is not descriptive of the size of a measurement it is often convenient to express this value as a percentage of the mean value. This expression has been called coefficient of variation.

A graphical representation of variations resulting from different compaction methods is shown in Figure 9 for one of the asphaltic concrete mixtures compacted by two operators. An examination of this figure as well as the data in the table indicates that a relationship existed between the value of density and the produce of pressure times number of gyrations, that is, the average density increased as this product increased. The amount of increase in density may not be very significant since this value was generally within the usual allowed density variation of ± 0.02 gm/cc. The data also show that for operator J.M. the density obtained by the standard THD method was the lowest, but for operator R.W. this density compared favorably with that resulting from the 31 psi-30 gyrations method. Of particular interest is the observation that the lowest coefficient of variation for density obtained is generally associated with the 31 psi-30 gyrations compaction method; however, most of the values of C.V. were below 0.5 percent.

The variabilities in density of the different specimens molded by the different operators does not appear to be correlated to method but it is affected by operator variable. The data however do show that density variability is reduced by modifying the standard THD compaction method to one in which the molding pressure is held constant and a fixed number of gyrations is employed.

The variations in Hveem stability apparently do not correlate to compaction method or density for all mixtures and the average stability values either increased or decreased in magnitude, depending upon the mixture, as the compactive effort (pressure times number of gyrations) was increased.



EFFECTS OF MOLDING METHODS ON VARIATIONS OF SPECIMEN DENSITY AND STABILITY ON MIXTURE 1774

FIGURE 9

TABLE 23

Effects of Molding Methods on Variabilities of Specimen Density and Stability of Various Mixtures

Operator		Standard		19 psi	30 g	19 psi	40 g	31 psi	30 g	31 psi	40 g
		D	S	D	S	D	S	D	S	D	S
		Phase III	Mixture-Hwy. 6-N.								
R. W.	n	6	6	6	6	6	6	6	6	6	6
	$\bar{x}$	2.390	43.8	2.390	45.6	2.406	43.3	2.411	45.8	2.413	39.2
	S	0.005	4.42	0.009	5.14	0.005	2.54	0.004	4.64	0.002	4.20
	C.V.	0.21	10.10	0.36	11.42	0.19	5.87	0.15	10.12	0.07	10.72
J. M.	n	3	3	3	3	3	3	3	3	3	3
	$\bar{x}$	2.364	45.0	2.381	42.7	2.388	41.3	2.396	40.7	2.405	41.0
	S	0.026	1.32	0.003	1.69	0.001	4.04	0.002	1.45	0.004	1.80
	C.V.	1.09	2.93	0.12	3.97	0.06	9.77	0.07	3.57	0.16	4.39
		Phase IV	Mixture-1774								
R. W.	n	6	6	6	6	6	6	6	6	6	6
	$\bar{x}$	2.286	45.1	2.271	44.2	2.285	44.4	2.296	52.7	2.299	44.50
	S	0.012	2.3	0.008	1.58	0.009	3.79	0.005	2.857	0.008	3.44
	C.V.	0.53	5.0	0.37	3.57	0.38	8.53	0.218	6.70	0.32	7.74
J. M.	n	3	3	3	3	3	3	3	3	3	3
	$\bar{x}$	2.257	43.2	2.264	44.2	2.271	44.5	2.275	45.5	2.285	45.7
	S	0.003	1.04	0.002	.765	0.001	0.292	0.002	0.5	0.0002	2.1
	C.V.	0.12	2.41	0.093	1.73	0.05	0.66	0.08	1.12	0.01	4.82
W. S.	n	6	6					3	3		
	$\bar{x}$	2.285	40.3					2.299	45.7		
	S	0.008	3.36					0.002	1.77		
	C.V.	0.34	8.36					0.07	3.88		
R. W.	n			6	6						
	$\bar{x}$			2.280	44.75						
	S			0.009	1.51						
	C.V.			0.39	3.37						
E. H.	n					4	4	3	3		
	$\bar{x}$					2.284	43.0	2.308	47.3		
	S					0.003	1.73	0.001	1.90		
	C.V.					0.10	4.02	0.06	4.01		

TABLE 23 (Cont.)

Phase V Mixture-Gifford Hill

Operator		Standard		19 psi	30 g	19 psi	40 g	31 psi	30 g	31 psi	40 g
		D	S	D	S	D	S	D	S	D	S
R. W.	n	6	6	6	6	6	6	6	6	6	6
	$\bar{x}$	2.343	39.3	2.351	41.3	2.351	37.2	2.357	43.1	2.362	40.4
	s	0.009	3.99	0.005	1.67	0.003	1.90	0.004	2.01	0.007	3.12
	C.V.	0.40	5.25	0.12	4.6	0.55	5.38	0.17	4.95	0.12	3.94
J. M.	n	3	3	3	3	3	3	3	3	3	3
	$\bar{x}$	2.445	45.0	2.549	45.0	2.495	45.16	2.458	42.5	2.461	45.5
	s	0.037	3.97	0.008	2.65	0.044	5.11	0.039	3.5	0.014	2.78
	C.V.	1.53	3.50	0.03	5.89	1.76	11.31	1.59	8.24	0.57	6.11
C. W.	n	6	6	6	6	6	6	6	6	6	6
	$\bar{x}$	2.342	40.0	2.341	38.92	2.344	37.92	2.350	39.58	2.362	38.92
	s	0.009	2.098	0.002	1.79	0.003	2.04	0.004	1.96	0.003	1.53
	C.V.	0.40	5.25	0.12	4.6	0.55	5.38	0.17	4.95	0.12	3.94

Phase VI Mixture-Iron Ore

R. W.	n	6	6	6	6	6	6	6	6	6	6
	$\bar{x}$	2.580	40.4	2.560	44.0	2.573	41.4	2.579	43.0	2.582	42.3
	s	0.007	3.94	0.010	2.05	0.006	4.8	0.001	0.61	0.010	2.73
	C.V.	0.26	9.75	0.39	4.66	0.23	11.61	0.05	1.42	0.38	6.45
J. M.	n	3	3	3	3	3	3	3	3	3	3
	$\bar{x}$	2.556	43.2	2.560	45.3	2.563	50.5	2.564	47.0	2.577	48.3
	s	0.005	1.04	0.009	4.48	0.009	1.80	0.003	4.36	0.009	2.09
	C.V.	0.18	2.41	0.33	9.88	0.36	3.56	0.12	9.28	0.34	4.32

The data show that the coefficient of variation for Hveem stability can normally be expected to be less than 10 percent for strengths values within the range obtained in this study or that 2 out of 3 stability values will be within 90 to 110 percent of the mean value.