Use of a Gyratory Testing Machine In Evaluating Bituminous Mixtures

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A study was made of selected laboratory test properties of bituminous mixtures compacted by the gyratory testing machine. This compaction was imposed in an attempt to simulate compaction by construction equipment and traffic. The study consisted, in part, of stability and unit weight measurement. Two aggregate gradations were used to study the effects of compaction on dense- and open-graded mixtures. Compactive effort was varied by changing ram pressure and number of revolutions, as well as type of operation in the gyratory testing machine. Statistical analyses were used to evaluate the effect of the machine variables on specimen stability.

The stabilities of specimens compacted in the gyratory testing machine were compared to those compacted in the kneading compactor according to the Hveem design procedure. Stabilities at the same percent voids were analyzed for both kneading- and gyratory-compacted specimens. Compacted specimens were cut in half and unit weight determinations were made for specimen tops and bottoms. Statistical tests were performed to determine whether unit weight gradients existed in compacted specimens.

The results of the study indicated that the load imposed on specimens during the course of the stabilometer test increased density and decreased voids in some compacted specimens. For the more dense mixture, increased initial compaction decreased the secondary compaction that could be applied before loss in stability occurred. For these mixtures, good correlation was noted between the stability values of kneading-compacted and gyratory- compacted specimens for the same percent voids. For the open-graded mixture, gyratory-compacted specimens had higher values of stability than did kneading-compacted specimens for the same percent voids.

Statistical analyses indicated that for the open-graded mixture, the tops of kneading-compacted specimens had appreciably higher unit weights than the bottoms. This relationship was not dependent on asphalt content. For gyratory-compacted specimens, unit weights of specimen bottoms tended to be slightly greater than those of specimen tops in cases where a difference in unit weight was noted.

Gyratory compaction of long slender, aggregate pieces dispersed in a plastic clay medium allowed reorientation of the aggregate so that the long axis of the aggregate pieces tended to be horizontal.

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BITUMINOUS MIX design methods in current use relate design to amount and type of traffic the pavement will be required to withstand (14). Because of varying and unknown traffic loads to which a bituminous pavement is subjected, design and construction criteria may have to be altered occasionally to provide a realistic correlation between laboratory design and in-service traffic conditions. The stability required for pavement at a signalized intersection on a primary truck route may be quite different from that required for a lightly traveled secondary highway. Rutting and shoving of bituminous resurfacing, particularly at signalized intersections (5), indicate that some bituminous mixtures are unstable in certain instances when present design methods predict the mixture should be stable. Evidently design methods in current use are not completely adequate.

Currently used laboratory compaction methods (1, 6) have not been able to reproduce the in-service density of some bituminous mixtures without producing excessive degradation. Type of compaction has been shown to be important to the strength that may be expected from a bituminous mixture (1, 2). Researchers (4, 12, 16, 17, 19, 20) in bituminous mixture design methods have indicated a need for reproducing in laboratory test specimens the same properties that the pavement will acquire when used by traffic.

There are disadvantages of prohibitive cost, unknown or uncontrollable variables, etc., which may hinder useful results of field testing (24) and cause gaps between laboratory designs and in-service traffic condition (8). Horizontal forces due to movement of the tire might be a main cause of difference between field and laboratory compaction (16). Also, laboratory procedures that achieve a given density without regard to aggregate orientation or degradation cannot produce representative specimens (15).

Field research in measuring pavement densification under traffic has found (13) that densification of a mix is proportional to the opportunity a mix has to densify. Soils investigations (26) have shown that steel-wheeled rollers produce the greatest density in a zone close to the roller surface. The Hveem design procedure (21) utilizes the kneading compactor to reproduce degradation and kneading effects similar to those occurring under traffic. Schmidt et al. (25) shows that for excessive compaction with steel-wheeled rollers, pavement density increases with depth from the pavement surface.

The gyratory shear method approximates the in-service pavement condition more closely than other compaction methods (20). In developing improved procedures for design and control of hot-mix bituminous pavements, the U. S. Army Engineer Waterways Experiment Station built a gyratory testing machine based on the compaction method used by the Texas Highway Department (17, 20, 22). This machine was used extensively in correlatory work with pavements subjected to high tire contact pressures (1, 11). It has also been used for density control of highway bituminous paving projects (9). Because the gyratory testing machine produces in laboratory specimens density and stability values approaching those that result from heavy aircraft traffic (1), it was studied for possible applicability to the simulation of highway construction and traffic effects on bituminous mixtures.

To relate the gyratory compaction procedure to one in current use, selected properties of gyratory-compacted specimens were compared with those of kneading-compacted specimens. Because mixture stability was considered one of the most important properties desired in a bituminous mixture, all machine variables were evaluated by their effect on this property.

EQUIPMENT AND TESTING METHOD

Equipment used in this study for the compaction and testing of bituminous mixtures is standardized equipment with the exception of the gyratory testing machine (Figs. 1, 2), which is a mechanized compaction and testing apparatus similar in principle to the manually operated Texas compaction apparatus. Compaction of a specimen occurs when the machine exerts a combined kneading and shearing action on a specimen contained in a steel mold. Vertical pressures are maintained against the specimen by hydraulically controlled steel rams whose faces are parallel to one another. The chuck holding the steel mold is mechanized so that it can move with the revolution of two

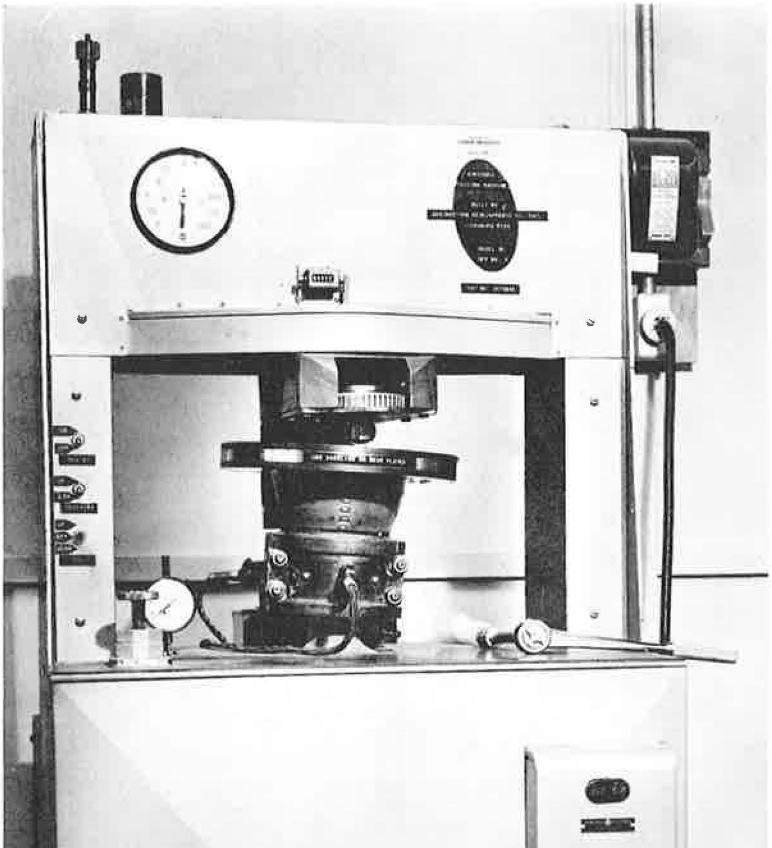
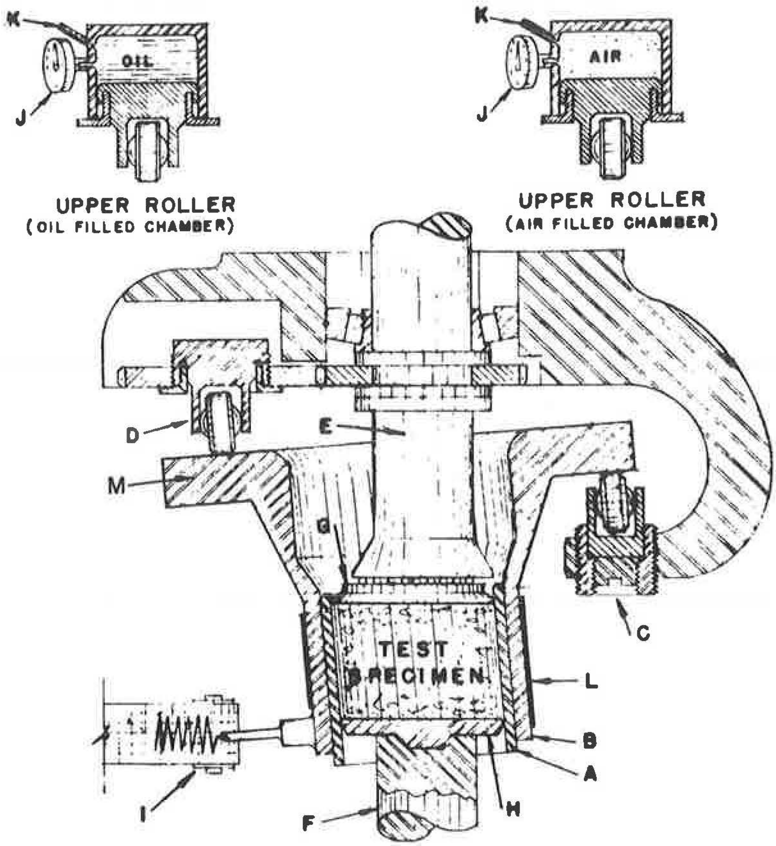


Figure 1. Gyratory testing machine.



A. Specimen Mold
B. Mold Chuck
C. Lower Roller
D. Upper Roller
E. Upper Ram Shaft
F. Lower Ram Shaft
G. Upper Head
H. Lower Head
I. Gyrograph
J. Pressure Gage
K. Filling Valve
L. Heating Element
M. Chuck Flange

Figure 2. Schematic side view of section through gyrating mechanism (after Corps of Engineers).

rollers, one on each side of the chuck flange. The lower roller is adjustable and permits the chuck flange to be rotated or pitched about its vertical axis.

Different degrees of gyratory action may be obtained by employing fixed, air-filled, or oil-filled upper rollers (Fig. 2). Most of the compaction in this study was accomplished using a fixed upper roller. The machine as operated with this roller produces gyratory action of the fixed-deformation type. A smaller number of tests were performed using the air-filled upper roller. This permits a fixed-stress variable-deformation gyratory action.

Although the pitch of the flange on a line connecting the rollers (which act as point loads 180^{0} apart) is fixed, the flange can rotate about the line between these two points, and therefore, the mold chuck can develop gyratory angles greater than the angle made by this line. Changes in the gyratory angle reflect the plastic properties of the material in the mold and are recorded on a gyrograph by a mechanical pen recorder. The more plastic and the weaker the specimen, the larger will be the gyratory angle and the wider will be the gyrograph.

The gyratory testing machine used in this study produced a compacted specimen with dimensions compatible for stability testing by several currently used design procedures (14). The Hveem stabilometer (3, 14, 21) was selected as the basis for stability evaluation of compacted specimens because Hveem stability values have had good cor-

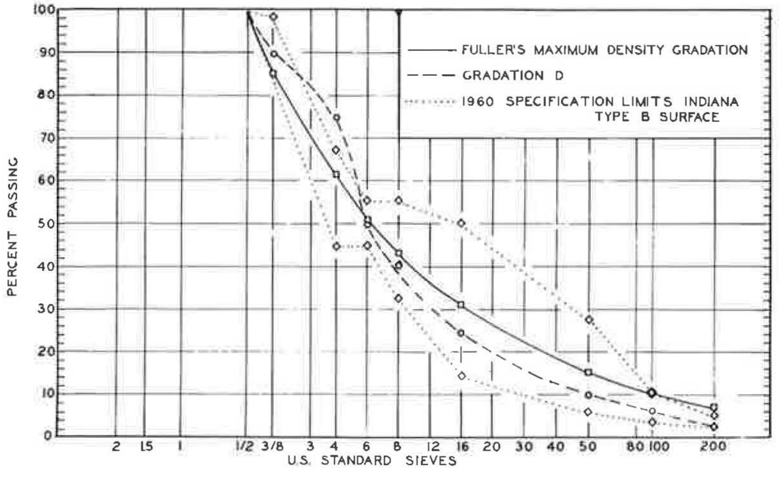


Figure 3. Aggregate gradation curves.

TABLE 1

RESULTS OF TESTS ON AGGREGATES

Material	Size	Spec. Gravity		Absorption (%)
		Bulk	Apparent	
Limestone	$\frac{1}{2}$ - $\frac{3}{8}$ in.	2.63	2.68	1.10
Limestone	$\frac{3}{8}$ - No. 4	2.67	2.71	0.90
Limestone	No. 4-6	2.63	2.71	1.74
Limestone	No. 6-8	2.62	2.70	1.94
Natural Sand	No. 8-16	2.59	2.72	2.77
Natural Sand	No. 16-50	2.60	2.70	2.45
Natural Sand	No. 50-100	2.63	2.70	2.63
Dune Sand	No. 100-200	2.59	2.65	1.27
Limestone	Passing No. 200	2.71	—	—

relation with field performance of bituminous mixtures. Hveem and Davis (7) believe that materials with varying stabilities do not undergo any marked difference in relative classification whether tested in the stabilometer or in a triaxial device where a theoretical stress analysis is possible. The stabilometer test is relatively fast and easy to perform and, hence, applicable to testing adequately a large number of specimens in a short time.

MATERIALS

The bituminous mixtures used for this study were selected according to specifications of the Indiana State Highway Commission for Hot Asphaltic Concrete Surface—Type B (10). It was thought that the gradations selected would make them applicable to testing in both the gyratory machine and the Hveem stabilometer without special modification of standard test procedures.

The types of aggregates used were crushed limestone, dune sand, natural sand and limestone filler. Aggregate materials were tested for specific gravity and absorption according to ASTM Methods C 127 and C 128. The results of these tests are given in

Table 1. The commercially produced and washed aggregates were sieved into the required sizes and then washed again before storage prior to blending.

The two gradations used in this study are shown in Figure 3. The Fuller's maximum density gradation utilized a ½-in. maximum sieve size and was calculated from the Fuller and Thompson empirical formula

$$P_i = P_o(D_i/D_o)^{1/2} \quad (1)$$

in which

P_i = percent smaller than D_i

P_o = percent smaller than D_o

D_o = maximum sieve size in gradation

D_i = intermediate sieve size in gradation

TABLE 2

RESULTS OF TESTS ON ASPHALT CEMENT

Spec. Grav. at 77 F	1.036
Softening Point, Ring and Ball (F)	124
Ductility at 77 F, 5 cm/min (cm)	200 +
Penetration, 100 gm, 5 sec at 77 F	66
Penetration, 200 gm, 60 sec at 32 F	17
Loss on Heating, 50 gm, 5 hr at 325 F (%)	0.01
Penetration of Residue (% of original)	89
Flash Point, Cleveland Open Cup (F)	595
Solubility in CCl_4 (%)	99.84

Gradation D material was similar to the Type B surface.

Results of tests on the 60 to 70 penetration grade asphalt used are presented in Table 2.

PROCEDURE

Aggregates separated into component sieve-size fractions were batched according to the blend formula. Aggregate batches of 1100 gm each were used throughout the study and batching was accomplished with cold dried aggregates using a scale sensitive to 1 gm. Prior to mixing, aggregate batches and asphalt were heated separately to 325 ± 5 F. Mixing bowl, paddle, and other utensils were also heated to 325 ± 5 F to minimize heat loss during mixing. Asphalt content for the entire study was specified as percent by weight of the aggregate. The constituents of each batch were mixed in a modified Hobart mixer for 2 min and then transferred to curing pans for a 15 hr period at 140 ± 5 F in a Hotpack oven provided with forced draft air circulation. After the curing period, each batch was reheated to 225 ± 5 F for compaction.

Two types of compaction were used in this study: kneading and gyratory. Kneading compaction was performed with the California kneading compactor using the procedure outlined by the Asphalt Institute (14).

The sequence of compaction in the gyratory testing machine was chosen to simulate compaction that might be expected from construction equipment and traffic. Accordingly, compaction in the gyratory testing machine was divided into two phases—initial compaction and secondary compaction. Initial compaction was carried out with the fixed upper roller and a specimen temperature of 225 ± 5 F. Either 10 or 20 initial compaction revolutions were imposed on the specimen in an attempt to bracket the range of compaction a bituminous layer might receive from construction compaction equipment. Ram pressures of 50, 100, and 150 psi were utilized.

Secondary compaction involved 30, 60, 90, or 400 additional revolutions at secondary pressures of 50, 100, or 150 psi and a temperature of 140 F. These pressures were selected to simulate normally severe tire contact pressures imposed by traffic.

After completion of compaction in either the gyratory testing machine or the California kneading compactor, specimens were tested in the Hveem stabilometer by the procedure outlined by the Asphalt Institute (14).

Bulk specific gravity determinations were made for all compacted specimens after stabilometer testing. Rice specific gravity was obtained for those specimens for which percent voids were to be computed. The procedure is detailed in ASTM Special Technical Publication No. 191 (23).

Uniformity of unit weight with specimen height was studied by cutting the compacted specimens in half with a masonry saw. Because the sawing operation wetted the speci-

TABLE 3

COMPARISON OF BULK UNIT WEIGHT BEFORE AND AFTER STABILOMETER TEST

Bulk Unit Weight (pcf)		
Before	After	Difference[1]
142.0	144.1	2.1
141.6	143.5	2.1
141.0	142.9	1.9
141.0	142.9	1.9
142.9	144.1	1.2
143.5	144.8	1.3
141.6	143.5	1.9
143.5	144.8	1.3
141.6	142.9	1.3
141.0	142.9	1.9
Total		16.7

[1]Mean difference = $\frac{16.7}{10}$ = 1.67 pcf.

men halves, they were washed free of dust and placed in water for a 24-hr absorption period. After the submerged and saturated surface-dry specimen weights were recorded, the specimen halves were placed on absorbent paper and air dried at room temperature for 24 hr. The weight in air was then recorded and specific gravity determinations were made.

RESULTS

Influence of Stabilometer Test on Compacted Specimens

Specimens tested in the Hveem stabilometer were deformed in the course of testing. To evaluate the effect of this deformation on the unit weight of compacted specimens, ten specimens were compacted in the gyratory testing machine using a 100 psi ram pressure, 10 rev., and a 1° angle of gyration. Bulk unit weights of these specimens were determined after compaction and after testing in the stabilometer and it was found that the stabilometer test caused a significant increase in these weights (Table 3).

Fixed-Roller Operation

To investigate the variation in stability caused by the factors involved in the gyratory compaction process an analysis of variance test was used. A series of three-way analysis variables included initial pressure, secondary pressure, and secondary revolutions. Two gradations, dense and open, were used to study effects of aggregate gradation and asphalt content was not varied. A total of 192 specimens containing 4 percent asphalt were tested by the procedures outlined previously, with the exception that only 30, 10, or 90 secondary revolutions were employed.

Four three-way analysis of variance tests were required to analyze data common to each of two gradations and two values of initial revolutions. A ranking of the relative

TABLE 4

ANALYSIS OF VARIANCE (FIXED EFFECTS MODEL)[a]

Factor[b]	Degrees of Freedom	Sum of Squares	Mean Squares	Variance Ratio	$F_{0.05}$	Decision[c]
A	2	58.39	29.20	7.19	3.89	Reject H_0
B	3	1198.76	399.59	98.42	3.49	Reject H_0
C	2	132.03	66.02	16.26	3.89	Reject H_0
AB	6	10.18	1.70	0.42	3.00	Accept H_0
AC	4	19.24	4.81	1.18	3.26	Accept H_0
BC	6	94.84	15.81	3.89	3.00	Reject H_0
ABC	12	48.74	4.06	—	—	—

[a]Fuller's maximum density gradation, 10 rev. initial compaction.

[b]A = secondary revolutions, 3 levels; B = secondary pressure, 4 levels; C = initial pressure, 3 levels.

[c]H_0: Stability not affected by factor (α = 0.05).

TABLE 5

ANALYSIS OF VARIANCE (FIXED EFFECTS MODEL)[a]

Factor[b]	Degrees of Freedom	Sum of Squares	Mean Squares	Variance Ratio	$F_{0.05}$	Decision[c]
A	2	75.95	37.98	15.76	3.89	Reject H_0
B	3	1197.34	399.11	165.61	3.49	Reject H_0
C	2	222.19	111.10	46.10	3.89	Reject H_0
AB	6	21.14	3.52	1.46	3.00	Accept H_0
AC	4	8.93	2.23	0.93	3.26	Accept H_0
BC	6	91.64	15.27	6.34	3.00	Reject H_0
ABC	12	28.95	2.41	—	—	—

[a]Fuller's maximum density gradation, 20 rev. initial compaction.
[b]A = secondary revolutions, 3 levels; B = secondary pressure, 4 levels; C = initial pressure, 3 levels.
[c]H_0: Stability not affected by factor ($\alpha = 0.05$).

TABLE 6

ANALYSIS OF VARIANCE (FIXED EFFECTS MODEL)[a]

Factor[b]	Degrees of Freedom	Sum of Squares	Mean Squares	Variance Ratio	$F_{0.05}$	Decision[c]
A	2	193.54	96.77	76.20	3.89	Reject H_0
B	3	1879.22	626.41	493.24	3.49	Reject H_0
C	2	160.97	80.49	63.38	3.89	Reject H_0
AB	6	74.77	12.46	9.81	3.00	Reject H_0
AC	4	5.79	1.45	1.14	3.26	Accept H_0
BC	6	6.68	1.11	0.87	3.00	Accept H_0
ABC	12	15.28	1.27	—	—	—

[a]Gradation D, 10 rev. initial compaction.
[b]A = secondary revolutions, 3 levels; B = secondary pressure, 4 levels; C = initial pressure, 3 levels.
[c]H_0: Stability not affected by factor ($\alpha = 0.05$).

TABLE 7

ANALYSIS OF VARIANCE (FIXED EFFECTS MODEL)[a]

Factor[b]	Degrees of Freedom	Sum of Squares	Mean Squares	Variance Ratio	$F_{0.05}$	Decision[c]
A	2	180.95	90.48	127.44	3.89	Reject H_0
B	3	1424.03	474.68	668.56	3.49	Reject H_0
C	2	310.16	155.08	218.42	3.89	Reject H_0
AB	6	45.08	7.51	10.58	3.00	Reject H_0
AC	4	1.46	0.37	0.52	3.26	Accept H_0
BC	6	19.03	3.17	4.46	3.00	Reject H_0
ABC	12	8.52	0.71	—	—	—

[a]Gradation D, 20 rev. initial compaction.
[b]A = secondary revolutions, 3 levels; B = secondary pressure, 4 levels; C = initial pressure, 3 levels.
[c]H_0: Stability not affected by factor ($\alpha = 0.05$).

TABLE 8

ANALYSIS OF VARIANCE (FIXED EFFECTS MODEL)
5-WAY CLASSIFICATION

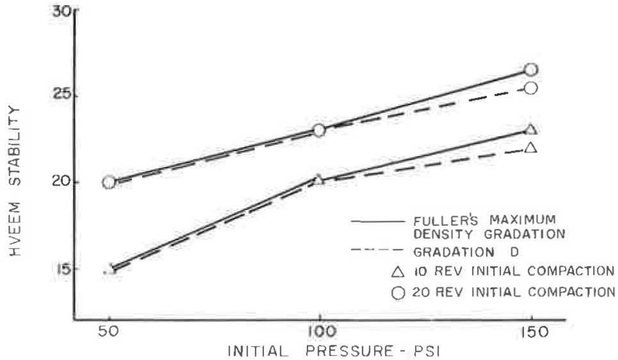
Factors	Mean Sum of Squares	Degrees of Freedom	F	$F_{60, 0.5}$	Decision[a]	Estimate of σ^2 Factor
Secondary revolutions	387.8	3	129.3	2.76	Reject H_0	8.0
Secondary pressures	279.2	3	93.1	2.76	Reject H_0	5.7
Initial pressures	475.8	2	237.9	3.15	Reject H_0	7.4
Initial revolutions	324.7	1	234.7	4.00	Reject H_0	2.4
Gradations	80.2	1	80.2	4.00	Reject H_0	0.8

[a]H_0: Stability not affected by factor (α = 0.05).

importance of the three factors in effecting changes in stability can be obtained from the size of the mean squares given in the last columns of Tables 4, 5, 6, and 7. Generally, for the increments chosen, the factors most important in increasing stability values were, in order of importance: secondary pressure, initial pressure, and secondary revolutions.

A five-way analysis of variance test (18) was then made (Table 8). It differed from the three-way analysis of variance in that it included also the factors of initial revolutions, gradations, and 400 secondary revolutions. A quantitative estimate of the importance of each factor may be obtained from the relative sizes of the numbers listed in the column headed "Estimate of σ^2 Factor." For this analysis, the factors most significant in changing specimen stability were, in order of importance: secondary revolutions, initial pressure, secondary pressure, initial revolutions, and gradation.

The ranking of factors in the five-way analysis of variance differed from the three-factor ranking most noticeably in the reversal of the importance of secondary pressure



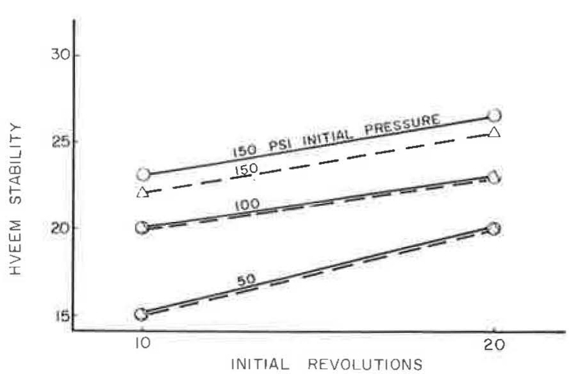


Figure 4. Effects of initial pressure and initial revolutions on specimen stability.

and secondary revolutions caused by the large (400) secondary revolutions value added to the levels of this factor. A controlled field study is necessary to determine how closely field compaction was simulated by the sequences of laboratory compaction.

The analysis of variance technique used here is a general method that may be used for investigating the effects of any number of variables on specimen properties. The estimate of σ^2 factor shown in the last column of Table 8 may be replaced in a more comprehensive study by estimates of regression for each factor. In this way linear, quadratic, and higher order effects of each factor could be measured. A computer analysis would be necessary for large-scale correlation between laboratory and field results.

Initial Compaction. —The effect of initial compaction pressure on initial stability of specimens is shown in a plot of Hveem stability vs initial pressure (Fig. 4). For this portion of the study a constant asphalt content of 4 percent was used. Increasing the

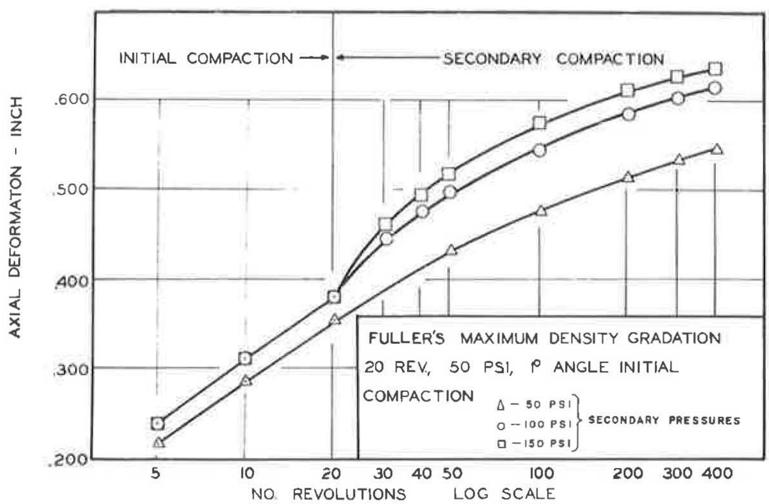


Figure 5. Axial deformation vs no. of revolutions, 50 psi initial compaction.

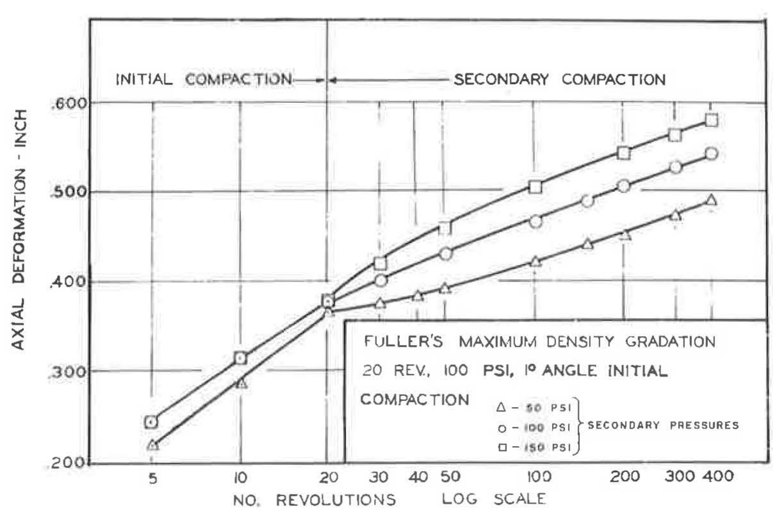


Figure 6. Axial deformation vs no. of revolutions, 100 psi initial compaction.

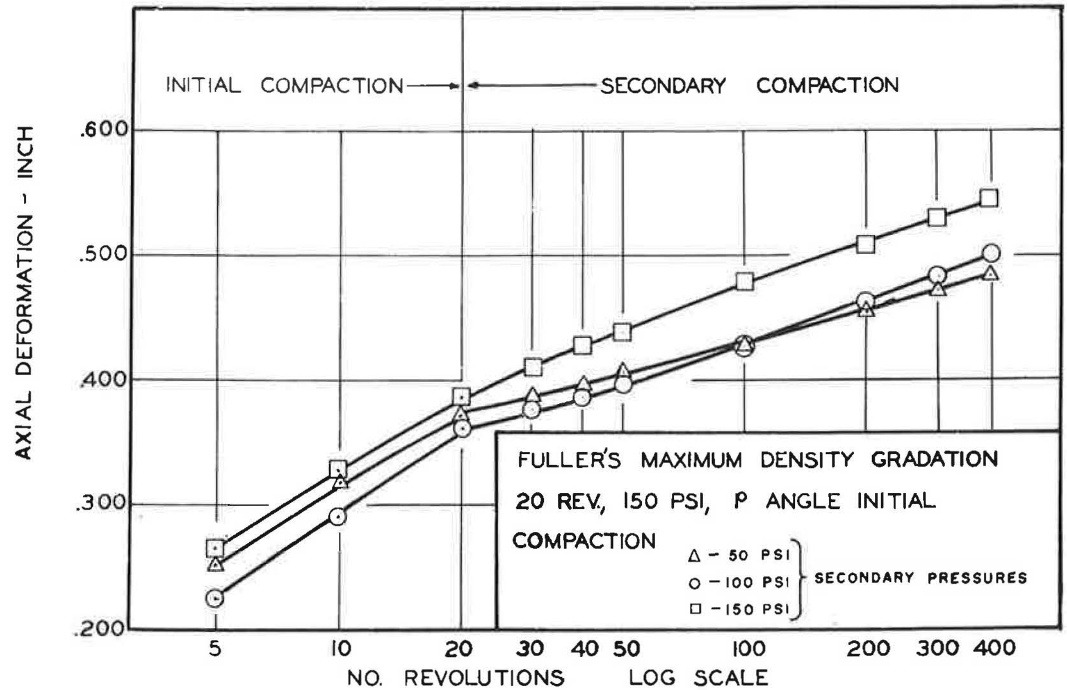


Figure 7. Axial deformation vs no. of revolutions, 150 psi initial compaction.

initial compaction pressure increased initial stability. Generally increasing pressure from 100 to 150 psi increased stability more than increasing pressure from 50 to 100 psi. Each point in Figure 4 represents the average of three stability values that differed from one another by less than 1½ stability units.

The plot of Hveem stability vs initial revolutions shown in the lower half of Figure 4 indicates that increasing initial revolutions from 10 to 20 increased initial stability. The slopes of the lines show that the increase in initial revolutions is most effective in increasing initial stability of specimens compacted at low pressure.

The confinement and deformation characteristics in the gyratory testing machine operating with fixed-roller conditions are different from those encountered in which deformation progresses. Under compaction equipment in the field, the layer of bituminous material becomes more dense. Accompanying this densification is an increase in bearing capacity and lateral support so that subsequent passes with compacting equipment cause successively smaller deformations. Compaction using the fixed-roller operation deforms the specimen by an angular amount at least equal to the gyratory angle, 1^0. Because this movement is greater than that produced by roller or traffic coverages, except perhaps for the first few roller passes, the progression of density and stability in the bituminous specimens is more rapid than that for pavement.

Secondary Compaction. —Figures 5, 6, and 7 may be interpreted as indications of rutting potential due to compaction under varying secondary compaction for mixtures compacted initially for 20 rev. at 1^0 angle using 50, 100 and 150 psi initial pressures. The semilog plots of axial deformation vs number of revolutions record axial deformation as the difference between specimen height when only a static load was applied and specimen height after some number of revolutions. The curves are concave downward only for secondary compaction pressures equal to or greater than the initial compaction pressure, indicating that the rate of axial deformation decreases during secondary compaction if initial compaction pressure exceeds secondary compaction pressure. High tire contact pressures might contribute considerably to densification in cases where initial compaction did not sufficiently densify the mix. In all cases observed in Figures

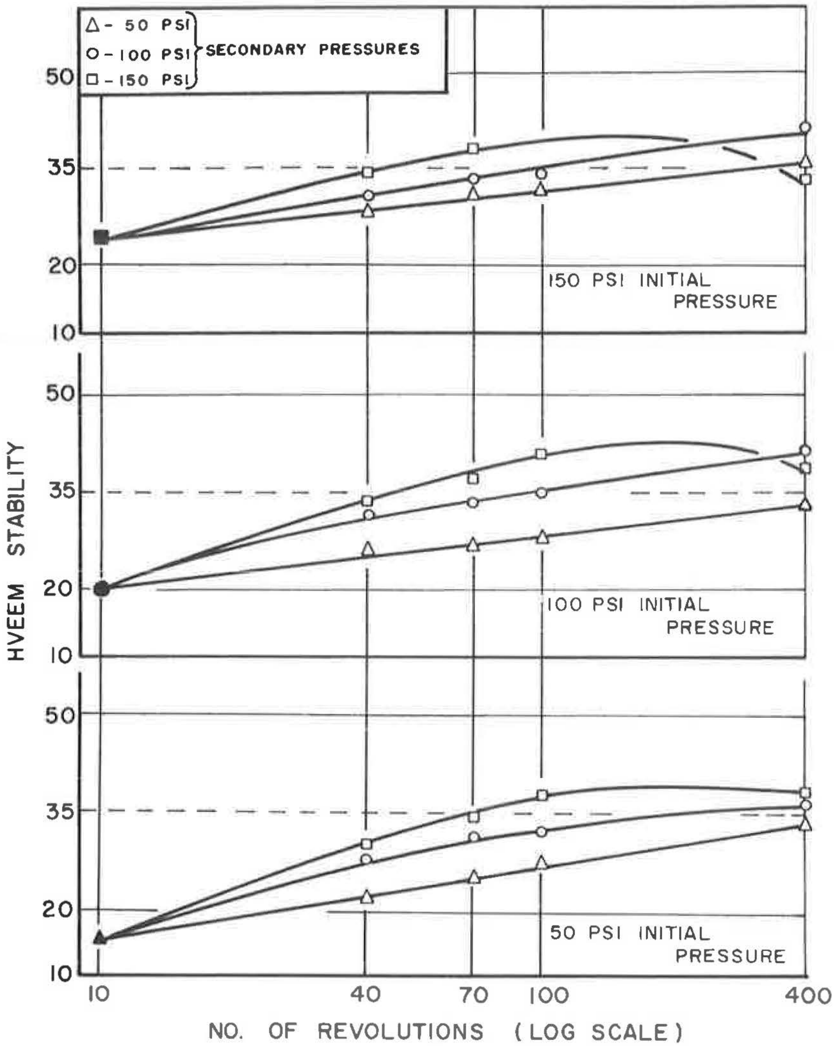


Figure 8. Hveem stability vs no. of revolutions, 10 rev. initial compaction, Fuller's maximum density gradation, 4 percent asphalt.

5 to 7, axial deformation increased, indicating that specimen confinement in the compaction mold was sufficient to prevent particle orientation that would have resulted in a decrease in unit weight.

The number of secondary revolutions was varied to simulate traffic coverages and to obtain an estimate of the variation of specimen stability with time under traffic. Figures 8, 9, 10, and 11 present semilog plots of Hveem stability vs number of revolutions for all 192 specimens compacted using fixed-roller operation. The solid black symbols in each figure represent the values of initial stability determined experimentally from the average of three stability measurements for each initial pressure—50, 100, and 150 psi. Other symbols represent only a single stability determination; however, duplicate determinations were made for those cases where a stability decrease occurred with additional revolutions. The graphs approximate straight lines for low pressures up to approximately 100 rev. and, thus, the relationship would be parabolic on an arithmetic plot.

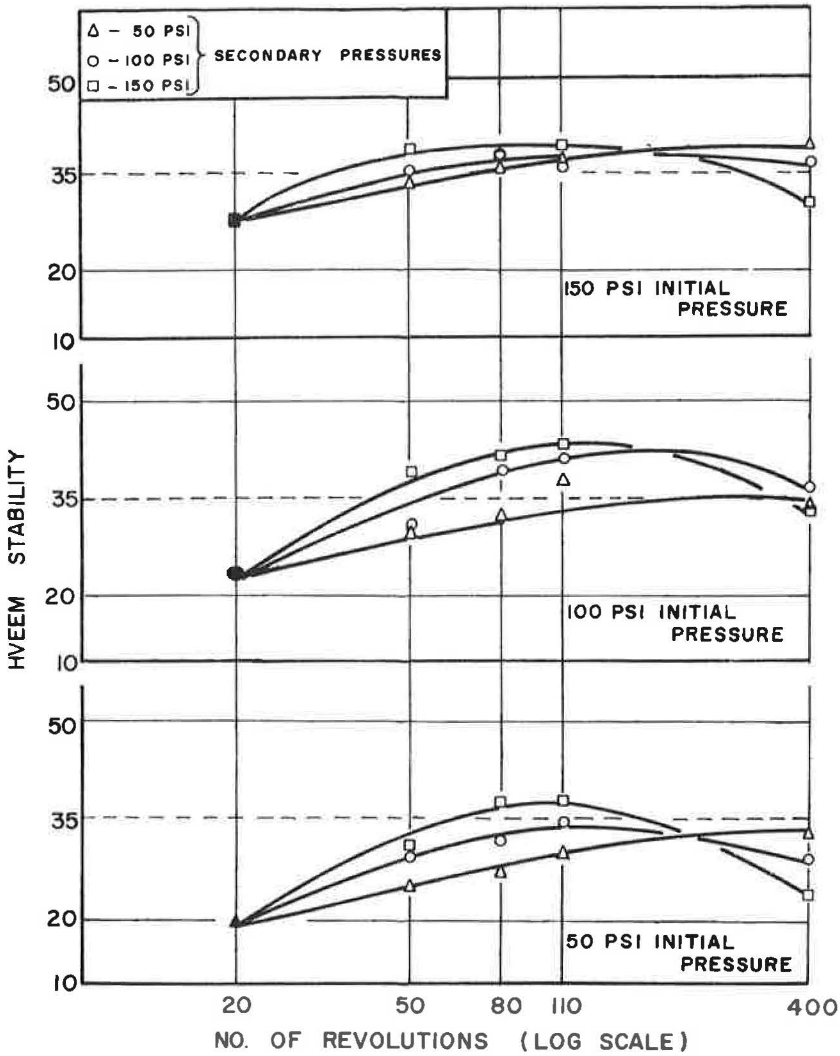


Figure 9. Hveem stability vs no. of revolutions, 20 rev. initial compaction, Fuller's maximum density gradation, 4 percent asphalt.

Gradation.—For gradation D (Figs. 10, 11) increasing revolutions increased stability, but for the Fuller gradation (Figs. 8, 9) stabilities for the high secondary pressures decreased with increasing secondary revolutions. This measurement may provide a relative index of resistance to loss of stability under traffic. For the Fuller gradation decreases in stability may be noted at the 400 rev. level for both 10 and 20 rev. initial compaction. In general, greater decreases in stability occurred in specimens compacted using higher secondary compaction pressures. This result should be expected from energy considerations, i.e., because compaction is an energy-consuming process the results of compaction should be measureable in energy units. Most specimens compacted initially for 20 rev. had somewhat lower stability values after 400 rev. than specimens compacted initially for 10 rev. Because the only difference between the 10 and 20 rev. initial compaction was the amount of compaction that occurred at the initial compaction temperature (225 F), it was concluded that the difference in compaction temperature was responsible for the apparent differences in stability and in resistance to loss in stability. No detailed attempt was made in this study to analyze the effects

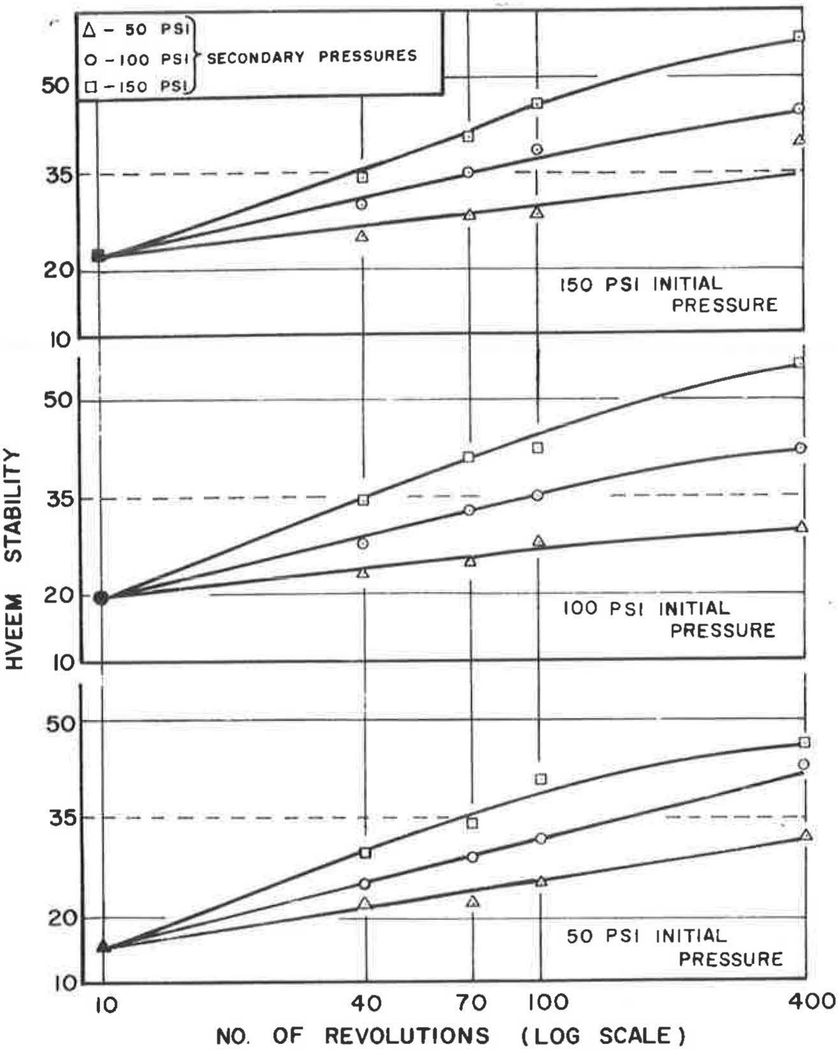


Figure 10. Hveem stability vs no. of revolutions, 10 rev. initial compaction, gradation D, 4 percent asphalt.

of compaction temperature on specimen stability; however, the stability difference observed indicates that some type of compaction temperature specification is necessary to insure uniformity of compaction. Asphalt in thin films exhibits a greater resistance to compaction at low than at high temperatures. For the Fuller gradation, increased initial compaction decreased the secondary compaction that could be applied before loss in stability occurred.

Design Procedures

Additional tests were performed to compare selected laboratory design test characteristics for gyratory- and kneading-compacted specimens.

Design of Dense-Graded Mixes. —Figure 12 presents a semilog plot of percent voids vs secondary number of revolutions for 20 rev. initial compaction of the Fuller gradation mixture with 4 percent asphalt. Comparison of Figure 12 with Figure 9 shows that when degree of compaction of this mixture is such that the void content is less than 2 percent, additional compaction will result in a decrease in stability. A good corre-

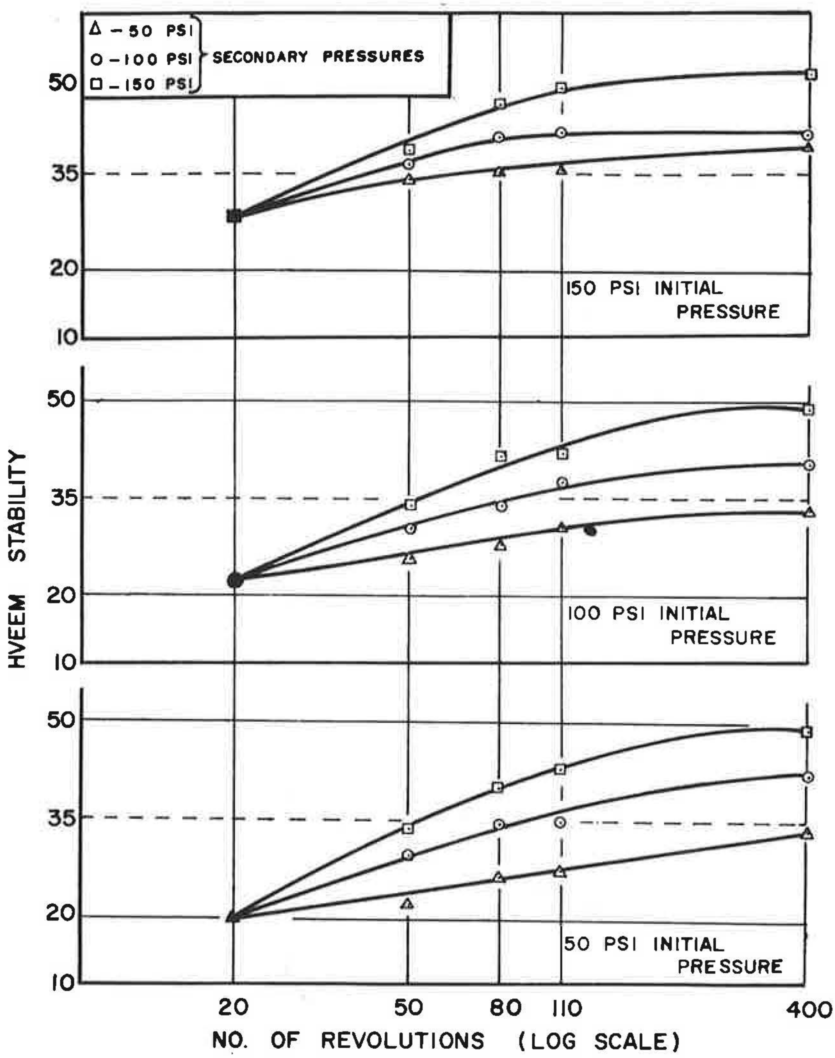


Figure 11. Hveem stability vs no. of revolutions, 20 rev. initial compaction, gradation D, 4 percent asphalt.

spondence between decrease of void value to less than 2 percent and widening of the gyrographs was also indicated. Some typical gyrographs are presented in Figure 13.

To relate the gyratory design technique to a standard design procedure, six specimens of the Fuller gradation were prepared by the standard kneading compaction technique specified in the Hveem design procedure. A plot of Hveem stability and percent voids vs percent asphalt (Fig. 14) indicates that 4 percent is the maximum asphalt content that this mixture can accommodate and remain stable under the compactive effort applied. Figures 8 and 9 reinforce this conclusion. The rather steep slope of the stability vs asphalt content curve (Fig. 14) indicates that the mix is quite sensitive with respect to amount of asphalt and infers mixture sensitivity with increased compaction. From this it was concluded that a design procedure utilizing the widening gyrograph concept was adequate for specifying asphalt content of dense-graded mixes.

Design of Open-Graded Mixes. --To study the possibility of using the gyratory testing machine to select an optimum asphalt content for open-graded mixes, 60 gradation D specimens varying in asphalt content from 4 to 7 percent were compacted in the

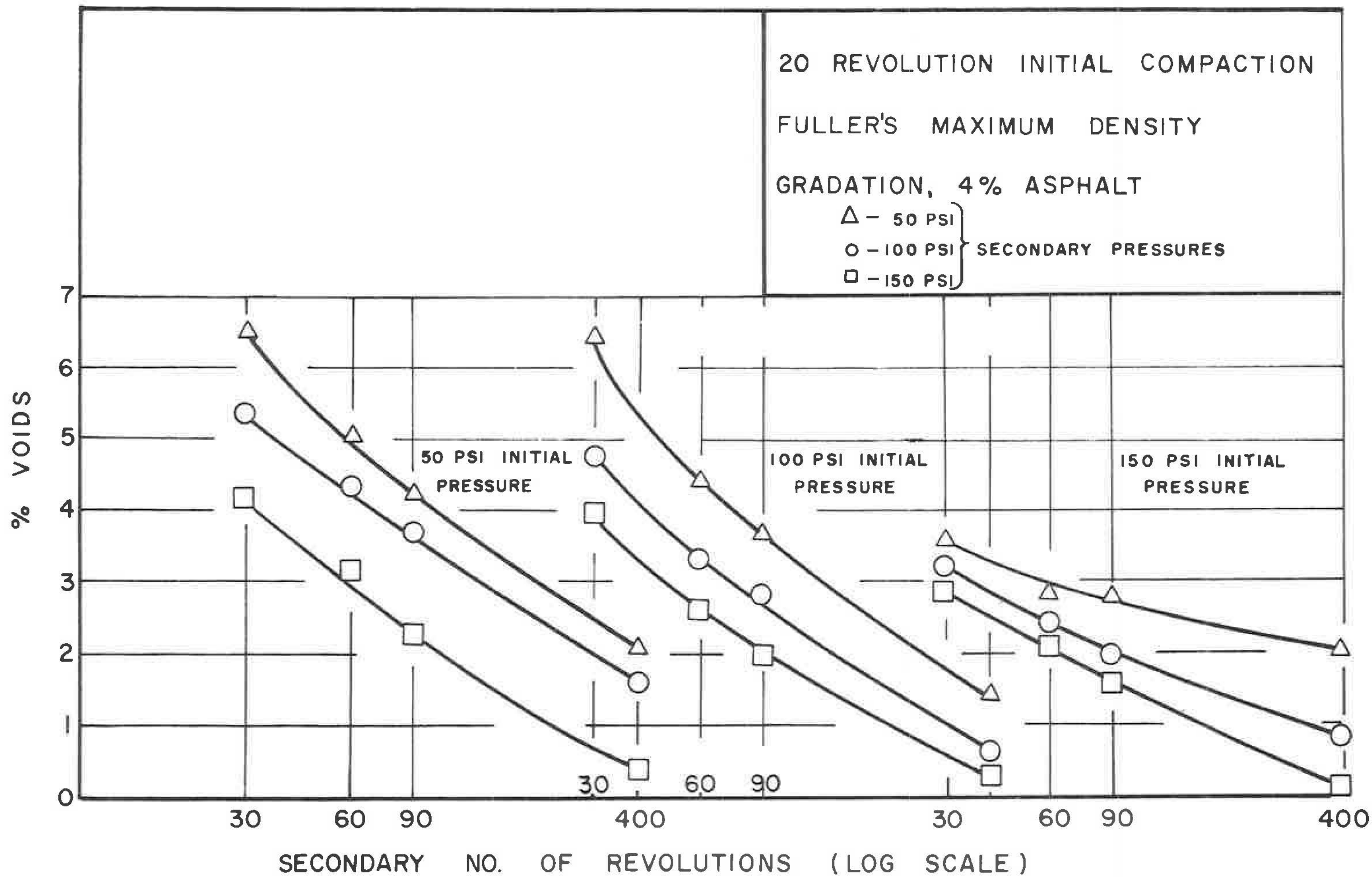


Figure 12. Percent voids vs no. of revolutions.

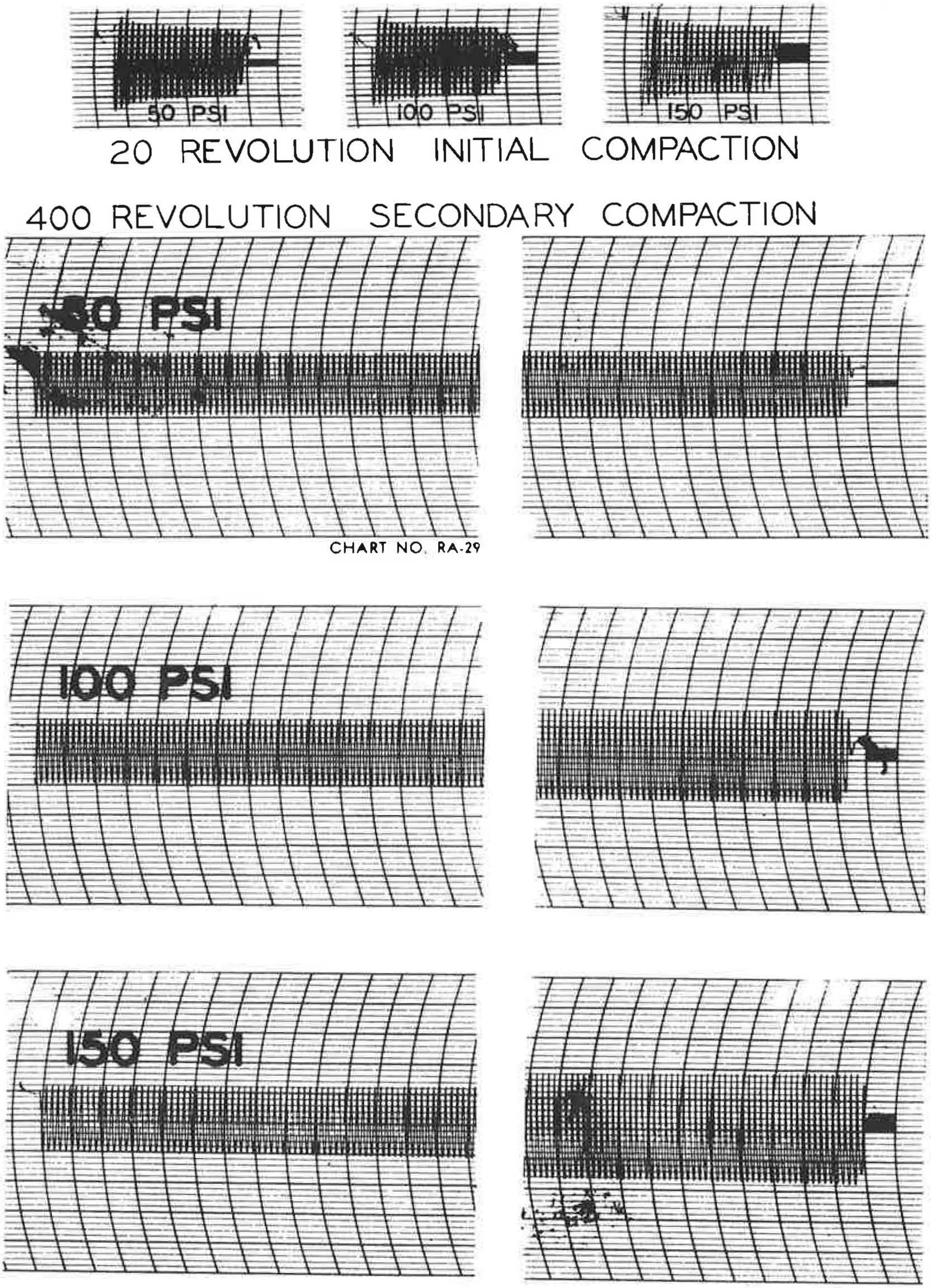


Figure 13. Typical gyrographs--fixed roller operation, Fuller's maximum density gradation.

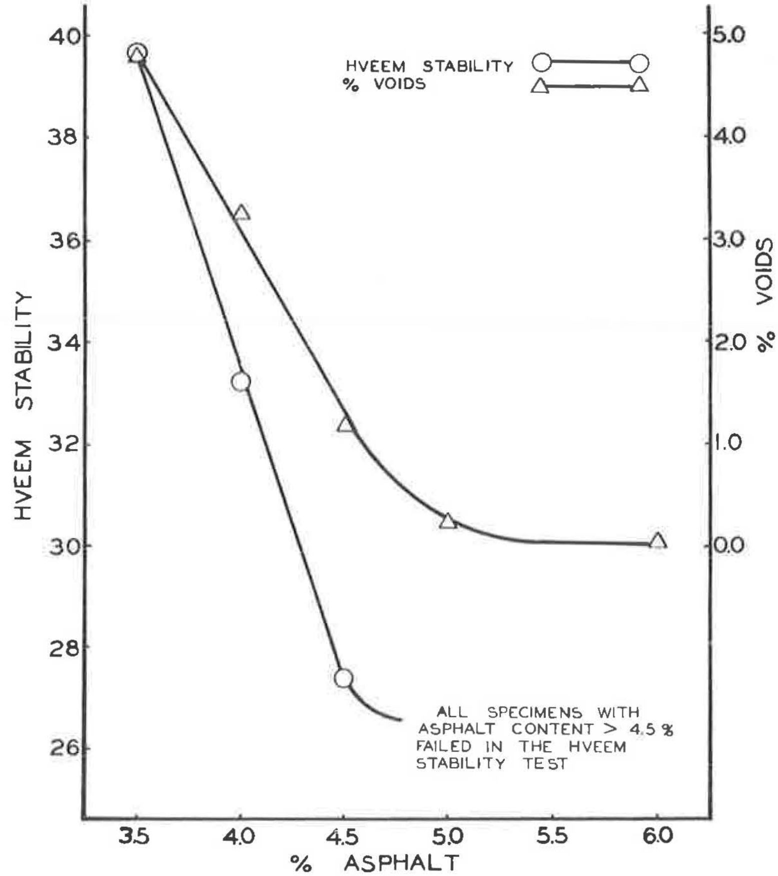


Figure 14. Hveem stability and percent voids vs percent asphalt, Fuller's maximum density gradation, kneading compaction.

gyratory testing machine and tested in the stabilometer. Figure 15 shows semilog plots of Hveem stability vs number of revolutions for these specimens. In each case stability values increased with increased number of revolutions; however, stability at 400 rev. decreased with increasing asphalt content for 150 psi secondary pressures. For all 60 specimens there was no widening of the gyrographs with increasing number of revolutions.

These results were also compared with those from four specimens compacted by the standard Hveem procedure. Figure 16 is a plot of Hveem stability and percent voids vs percent asphalt which can be compared to Figure 14. Stability values for kneading-compacted specimens shown in Figure 16 are much lower than the maximum stability values shown in Figure 15 for gyratory-compacted mixtures of the same composition. No indication of a critical asphalt content was evident from either stabilometer values or widening gyrographs for specimens of gradation D compacted by gyratory compaction up to 400 rev.

Figure 16 shows that an asphalt content of 5.5 percent is required for gradation D to obtain the 4 percent voids generally desired in the Hveem design procedure. However, 5.5 percent asphalt would yield a stability of only 24, less than that required for light traffic by Hveem criteria. Values of percent voids in Table 9 for gradation D gyratory-compacted specimens of 6 percent asphalt were 3.7, 3.2, and 2.4 percent, respectively, for secondary pressures of 50, 100, and 150 psi and 400 rev. Figure 15 shows that this compactive effort yields stabilities of 35 to 45. For this same range of percent voids, Figure 16 shows that kneading compaction yields stabilities of less than 30.

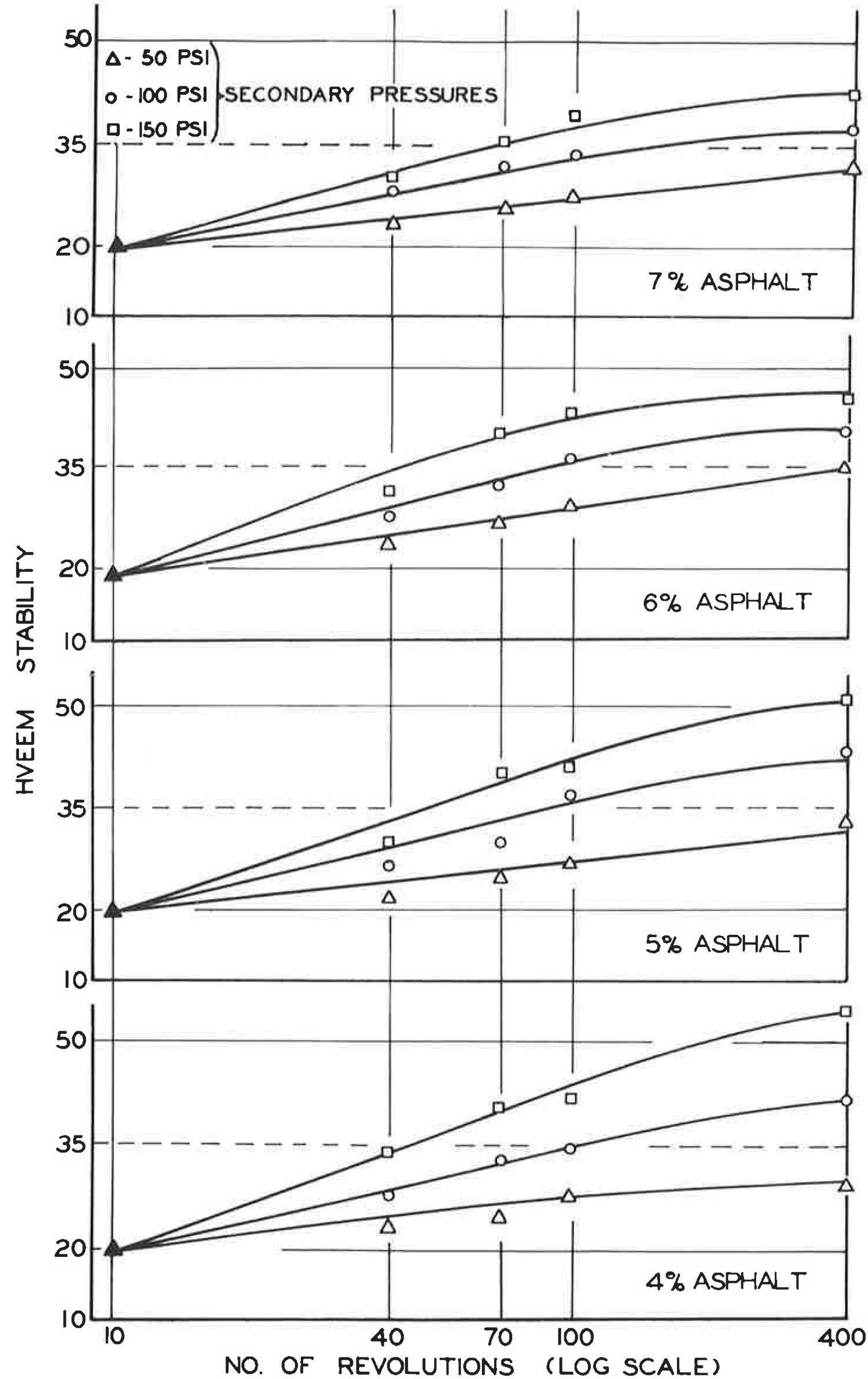


Figure 15. Hveem stability vs no. of revolutions, 10 rev., 100 psi initial compaction, gradation D, varying asphalt content.

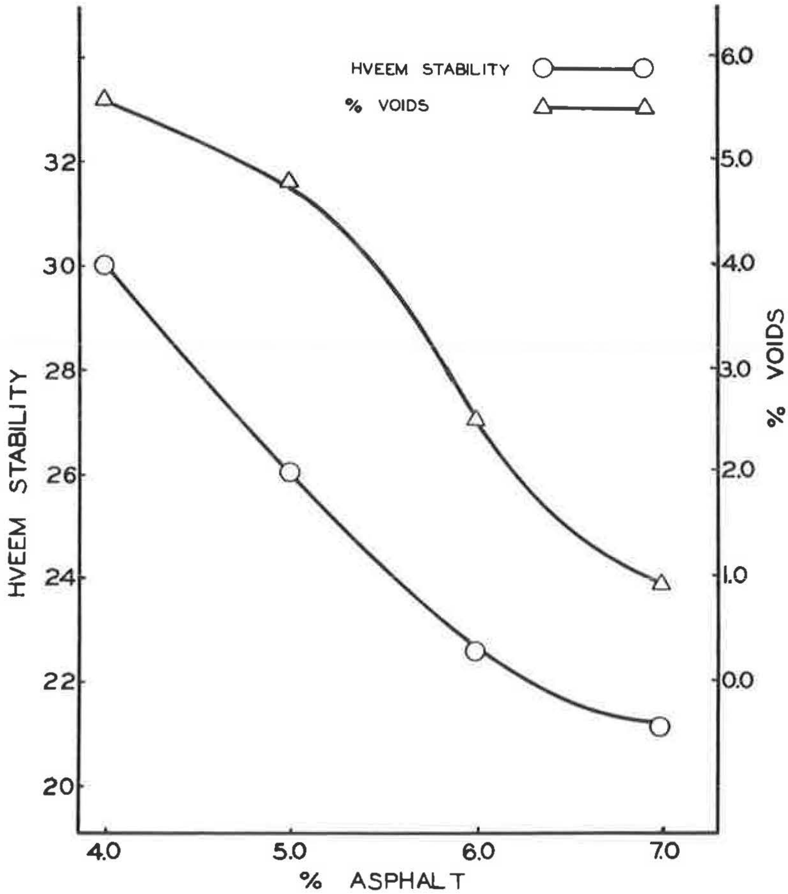


Figure 16. Hveem stability and percent voids vs percent asphalt, gradation D, kneading compaction.

Variation of Unit Weight with Specimen Height

By way of possible explanation for the difference in results obtained by kneading and gyratory compaction of the more open gradation, it should be noted that the high kneading foot pressures specified by the Hveem design kneading compaction procedure produced considerable degradation in specimen tops. Although the percent voids in specimens compacted by the two machines might be equal, this could represent an average of a low-void mix in the top and a high-void mix in the bottom of the kneading-compacted specimens.

To support this theory, statistical analyses were made of variation in unit weight with specimen height for kneading- and gyratory-compacted specimens. Eighteen gradation D specimens containing 4 percent asphalt were compacted in the gyratory testing machine using 10 rev. of fixed-roller operation at 100 psi and a 1° angle of gyration. The 18 specimens were then divided into two groups of nine specimens each. The first group received secondary

TABLE 9

PERCENT VOIDS FOR GRADATION D[a]

Secondary Pressure (psi)	Secondary Revolutions			
	30	60	90	400
50	8.1	7.4	6.5	3.7
100	6.9	5.7	4.9	3.2
150	5.7	4.9	4.1	2.4

[a]Six percent asphalt, 10 rev., 100 psi initial compaction.

TABLE 10

UNIT WEIGHT GRADIENT
OF GYRATORY-COMPACTED SPECIMENS[a]

Secondary Compaction at 1°		Bulk Unit Weight (pcf)		
Psi	Revolutions	Top	Bottom	Top-Bottom
50	60	137.3	136.0	1.3
100	30	137.9	137.3	0.6
100	60	138.5	138.5	0.0
100	90	138.5	137.9	0.6
150	30	136.0	138.5	-2.5
150	60	141.0	140.4	0.6
150	90	140.4	141.0	-0.6
—	—	134.2	132.3	1.9
—	—	134.2	135.4	-1.2

[a]Gradation D, 10 rev., 100 psi, 1° initial compaction, 4 percent asphalt.

TABLE 11

UNIT WEIGHT GRADIENT
OF GYRATORY-COMPACTED SPECIMENS[a]

Pressure (psi)		Bulk Unit Weight (pcf)		
Initial	Secondary[b]	Top	Bottom	Top-Bottom
50	50	141.4	143.1	-1.7
50	100	145.3	147.1	-1.8
50	150	147.0	149.8	-1.8
100	50	144.6	148.0	-3.4
100	100	146.6	148.8	-2.2
100	150	148.2	149.8	-1.6
150	50	145.0	146.0	-1.0
150	100	146.1	147.3	-1.2
150	150	149.6	148.8	0.8

[a]Gradation D, 10 rev., 1° initial compaction, 4 percent asphalt.
[b]At 1° and 390 rev.

compaction up to a maximum of 90 rev. Specific compaction conditions for each specimen are given in Table 10. Data showed that differences in bulk unit weights between specimen tops and bottoms were insignificant.

The second group of nine specimens received 390 secondary revolutions under conditions of fixed-roller operation at the pressures given in Table 11. For this group of specimens, specimen bottoms had higher unit weights than specimen tops. The average difference was 1.56 pcf. Gradation D was used for this test because the more open mixture might reflect more markedly the existence of a unit weight gradient.

Unit weight gradient of seven specimens compacted in the gyratory testing machine using the air-filled upper roller was also studied. For this type of operation, specimen bottoms were, on the average, 1.1 pcf heavier than specimen tops (Table 12).

TABLE 12

UNIT WEIGHT GRADIENT OF GYRATORY-COMPACTED SPECIMENS[a]

Secondary Compaction Pressure[b] (psi)		Bulk Unit Weight (pcf)		
Ram	Air	Top	Bottom	Top-Bottom
50	25	138.5	139.8	-1.3
100	25	138.5	138.5	0.0
150	25	137.3	138.5	-1.3
50	50	140.4	141.6	-1.2
100	50	143.5	144.1	-0.6
50	12	135.4	137.9	-2.5
100	12	136.0	136.7	-0.7

[a]Gradation D, 10 rev., 50 psi, 1° initial compaction, 4 percent asphalt.
[b]Four hundred rev. with air-filled upper roller at variable angle.

For kneading-compacted specimens, unit weight gradient was studied by compacting six gradation D specimens in the kneading compactor using the standard Hveem design compaction procedure. Asphalt contents for these specimens were varied in 0.5 percent increments from 4 to 6.5 percent. For all kneading-compacted specimens the unit weight of specimen tops exceeded the unit weight of specimen bottoms. Results (Table 13) show that the average difference in bulk unit weight was 6.0 pcf and the range was 3.7 to 8.1 pcf. Appearance of the compacted specimens ranged from a powdery, crushed upper surface for the specimen containing 4 percent asphalt to a flushed upper surface for the specimen containing 6.5 percent. No trend relating unit weight gradient and asphalt content was observed.

These results show that type of compaction is important in that it may effect the development of a unit weight gradient; reproduction of unit weight for design purposes must consider the unit weight gradient if an accurate laboratory simulation of the field condition is to be obtained.

Particle Orientation

The effect of gyratory compaction on particle orientation was studied by placing selected pieces of long, slender aggregate, with long axes vertical, in a plastic clay in the gyratory mold. These samples were then compacted for 400, 1,200, and 5,400 rev. using the fixed 1° upper roller in the gyratory testing machine. The gyratory compaction reoriented the aggregate particles into positions where their long axes lie horizontal (Figs. 17, 18), and the aggregate forms concentric circles in this reoriented position. The opportunity for reorientation would be greater in a plastic clay than in an aggregate mix where there is either particle-to-particle contact or particle separation by thin plastic films. Within the limits imposed by these conditions and the confinement of the compaction mold, particle orientation qualitatively similar to that which occurs under traffic appears possible using the gyratory shear method of compaction.

TABLE 13

UNIT WEIGHT GRADIENT OF KNEADING-COMPACTED SPECIMENS[a]

Asphalt Content (%)	Bulk Unit Weight (pcf)		
	Top	Bottom	Top-Bottom
4	146.0	138.5	7.5
4½	147.3	142.9	4.4
5	148.5	142.3	6.2
5½	148.2	142.3	5.9
6	151.0	142.9	8.1
6½	148.5	144.8	3.7

[a]Gradation D.

SUMMARY OF RESULTS AND CONCLUSIONS

The following results and conclusions, derived from the experimental data collected,

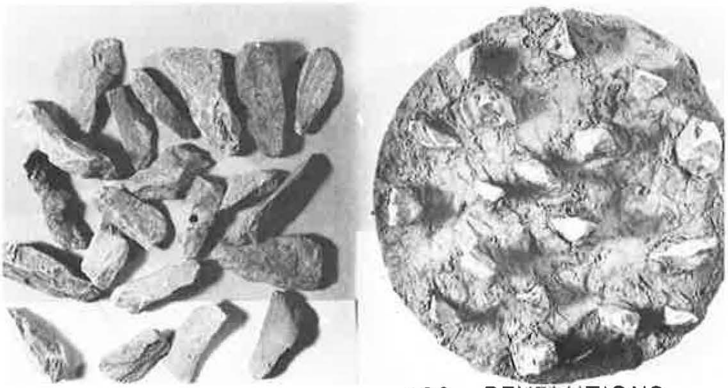


Figure 17. Study of particle orientation.

Figure 18. Study of particle orientation.

are applicable to the materials and testing procedures of this specific research only and may not be extended beyond these limits without appropriate correlation.

1. For the specimens of the Fuller gradation with 4 percent asphalt subjected only to simulated construction compaction in the gyratory testing machine and tested in the Hveem stabilometer, a significant increase in bulk unit weight was effected by the compression imposed on the specimens during testing in the stabilometer. The average increase was 1.67 pcf.

2. Analysis of variance for the five main factors studied showed all factors were statistically significant in affecting specimen compaction as evaluated by change in stability. Factors in order of importance were: secondary revolutions, initial pressure, secondary pressure, initial revolutions, and gradation. Data from controlled field studies are necessary to determine if a realistic simulation of the pavement condition is effected by this laboratory procedure. However, the same statistical methods can be applied to a field study for an evaluation of field compaction and stability variables.

3. In all cases studied, including both the dense and open gradations at all asphalt contents, increases in initial compaction pressure and number of revolutions increased the initial stability. Increased initial compaction decreased the secondary compaction that could be applied before loss in stability occurred.

4. Axial deformation of specimens under simulated traffic was greater for specimens initially compacted at high pressures. No decrease in unit weight occurred during compaction; confinement in the compaction mold was sufficient to prevent this.

5. Good correlation was obtained between widening of the gyrograph and loss in Hveem stability for the mixture employing the Fuller gradation. Stability values for kneading- and gyratory-compacted specimens compared favorably for the same values of percent voids. Hence, it is indicated that for this laboratory study, good stability and voids correlations were obtained for the dense mix compacted by the kneading compactor and the gyratory testing machine.

6. For gradation D, stability values of kneading-compacted specimens were lower than the stability values of gyratory-compacted specimens when both types had the same percent voids. High stability values were measured for gradation D specimens containing 4 to 7 percent asphalt and compacted to 400 rev. No indication of loss of stability was observed from the widening of the gyrographs. Kneading-compacted specimens of the same open-type gradation had stability values of 30 or less for the 4 to 7 percent range of asphalt content studied. For gyratory- and kneading-compacted specimens, marked differences in stability were attributable to differences in the type of compaction imposed on the specimens. A thorough study of the factors responsible for this discrepancy with respect to the gradation D mixture was not undertaken.

7. Gradation D specimens containing 4 percent asphalt and compacted in the gyratory testing machine had variation in unit weight from top to bottom differing with amount of compaction. Unit weights of specimen bottoms tended to be slightly greater than those of specimen tops.

8. For gradation D specimens with varying asphalt content, kneading compaction as specified in the Hveem design procedure produced specimens whose unit weight increased markedly from bottom to top.

9. Stability values for specimens compacted by the gyratory machine were found to be a function of temperature and mixture composition. Both mixture gradation and asphalt content were factors of composition influencing stability values.

10. Compaction of a plastic clay containing hand-placed pieces of slender aggregate showed that gyratory compaction allowed pieces to orient themselves into horizontal position in a pattern of concentric circles.

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