**STABILITY RELATIONSHIPS
OF GYRATORY-COMPACTED
BITUMINOUS MIXTURES**

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Research
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**PURDUE UNIVERSITY
LAFAYETTE INDIANA**

by

H. W. BUSCHING

Final Report

STABILITY RELATIONSHIPS OF GYRATORY-COMPACTED BITUMINOUS MIXTURES

TO: K. B. Woods, Director
Joint Highway Research Project

September 27, 1963

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

Project: C-36-6S
File: 2-4-19

Attached is a Final Report entitled "Stability Relationships of Gyratory-Compacted Bituminous Mixtures" authored by Mr. Herbert W. Busching, a Graduate Fellow on our staff. Mr. Busching performed the research under the direction of Professor W. H. Goetz and also used the report as his Thesis for the MSCE degree.

This project was approved by the Board on April 11, 1962. As Mr. Busching was on fellowships granted by the National Petroleum Refiners Association and the McMahon Construction Company no salary costs were involved for this research and the only cost to the Project was that of supplies, some extra labor and duplication of the report.

The report is presented to the Board as information and for the record. The information in the report was also made available to the National Petroleum Refiners Association.

Respectfully submitted,

Harold L. Michael
Harold L. Michael, Secretary

HLM:bc

Attachment

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by

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File No: 2-4-19

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Purdue University

Lafayette, Indiana

September 27, 1963

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ABSTRACT

Busching, Herbert W., MSCE, Purdue University, June, 1963.

Stability Relationships of Gyratory-Compacted Bituminous Mixtures.

Major Professor: William H. Goetz.

A laboratory study was made of the stability relationships of bituminous mixtures compacted in the gyratory testing machine.

Compaction in the gyratory testing machine was imposed on the bituminous mixtures in an attempt to simulate compaction that would be imposed by construction and traffic compaction. The study consisted, in part, of stability measurement of specimens compacted under varying levels of simulated construction and traffic compaction. 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. Stability measurements were made with the Hveem stabilometer.

Statistical analyses were used to evaluate the effect of each of the 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 % voids were analyzed for both kneading- and gyratory-compacted specimens.

Specimens compacted in the machines were cut in half and unit weight determinations were made for specimen tops and bottoms. Statistical

analyses were performed to determine whether unit weight gradients existed in the compacted specimens. Particle orientation was studied by dispersing long, slender aggregate pieces in a plastic clay media.

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 the dense-graded mixture, good correlation was noted between the stability values of kneading-compacted and gyratory-compacted specimens for levels of equal % voids. For the open-graded mixture, gyratory-compacted specimens had higher values of stability than did kneading-compacted specimens for the same % voids.

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

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

INTRODUCTION

Bituminous mix design methods in current use attempt to relate design to the amount and type of traffic the pavement will be required to withstand (21). Because of the varying and unknown traffic loads to which a bituminous pavement is subjected, design and construction criteria may have to be altered to provide a realistic correlation between the laboratory design and the in-service traffic conditions.

In recent years bituminous mixtures have been widely used in resurfacing deteriorated portland cement concrete pavements. Rutting and shoving of the bituminous resurfacing, particularly at signalized intersections, indicate that the bituminous mixture is unstable in certain instances. This instability is sometimes evident even when present design methods predict the mixture should be stable. Evidently design methods in current use are not completely adequate.

An asphalt content is established in currently-used design methods that yields maximum durability at some required stability level. Pavement stability requirements are functions of both type of load and pavement location. For example, trucks braking for a signalized intersection may increase local stability requirements. Redesigning a mixture to increase stability at this particular location may result in decreased durability elsewhere.

Under the compactive action of traffic bituminous pavements are subject to a large densifying force. After many coverages of heavy vehicles

a pavement may achieve a density greater than that obtained during construction. Because compaction is the best way of increasing the strength of granular materials, it would seem to be an important factor in the design of bituminous mixes. Particularly, the initial or construction compaction which determines initial resistance to deformation under traffic would seem to be of primary importance in approaching a realistic laboratory design.

A pavement that suffers distress by rutting might possibly suffer less if it received more initial compaction. Conversely, pavements which shove under braking and accelerating traffic at intersections would probably not be improved by additional construction compaction but might have to be specially designed so that excessive asphalt would not cause plastic deformation.

From these considerations it would seem useful to undertake a laboratory study to determine how the stability of a bituminous mixture varies under simulated traffic with the level of compaction achieved during construction.

Because the gyratory testing machine has shown it can produce in laboratory specimens density and stability values approaching those that result from heavy aircraft traffic, it was decided to use this machine in the simulation of highway construction and traffic effects. To date the gyratory testing machine has had only limited application in the field of highway mix design. It was thought that a laboratory study using the gyratory testing machine for specimen compaction would reflect not only on the relationship between stability and compaction, but would also give indication of the value of the gyratory testing machine as a testing machine and a highway traffic simulator.

To relate the gyratory testing machine and its compactive procedure to currently-used compaction techniques, it was decided to use the Hveem stabilometer to test specimens compacted in the gyratory testing machine. This would make possible a comparison of the stability values produced by the gyratory machine during traffic simulation with those produced by the California kneading compactor in the Hveem method of design. Data collected in the laboratory were used to relate this laboratory-based study to the Hveem design procedure and perhaps will form the basis for a future pavement service correlation study.

REVIEW OF LITERATURE

Within the past two decades highway transportation has increased and with it the need for more adequate pavement surfaces. Flexible bituminous pavements have been used extensively for new construction and for the resurfacing of deteriorated portland cement concrete pavements. Distress in areas where heavy traffic stress concentrations occur has indicated the need for a reexamination of bituminous mixture design. Wood and Goetz (33) state the problem:

Field performance indicates that extreme conditions of loading for a bituminous layer occur during summer climatic conditions under a stationary load or at locations where heavy trucks with high tire pressures undergo slowing or stopping movements. The plastic component of deformation under these conditions assumes major importance. The proper mixture design should minimize this component.

While it is important that a mixture should have sufficient stability under the above conditions, it must be remembered that winter temperatures impose a situation upon the mixture such that it acts like an elastic body. Under low temperatures, the mixture could become quite brittle.

Researchers (24) (25) (26) in the bituminous design methods have indicated a need for reproducing in laboratory test specimens the same properties that the pavement will acquire when used by traffic. Nevitt (23) has stated, "Design, or the evaluation of any proposed mix must be based on a test of a sample which simulates actual road conditions, rather than varying criteria based on a standardized test."

Goetz (8) has stated, "...the most important phase of the present design problem is not how to test a laboratory specimen, but how to form a laboratory specimen that represents the mixture as it is used in ser-

vice." Nevitt, McRae, and Philippi (23) (19) (25) have emphasized that laboratory specimens must be compacted to approximate the density of the prototype pavement. Nevitt (23) remarks, "...the compaction technique which does not give the same results as pavement consolidation with any type of mix poses a threat to the discovery of the actual condition that will appear in time."

Large compactive forces in the form of many repetitions of heavy axle loads or heavy aircraft gear have produced densities in bituminous highway and airport pavements which exceed those predicted by current laboratory methods (4). Accompanying this increased density has been a decrease in air voids and a corresponding decrease in stability reflected by rutting or shoving.

Nevitt (23) describes the types of compaction to which a bituminous pavement is subjected:

Construction compaction usually has as its objective merely sufficient densification to permit the subsequent use of the pavement without damage. Traffic compaction is that which results after construction. Experience shows that practically no construction compaction is sufficient to prevent further densification under traffic whenever the conditions are favorable.

A bituminous pavement is a three-phase system composed of aggregate, asphalt, and air. After construction compaction there is a relatively large space in the aggregate framework for the asphalt. During traffic compaction the aggregate particles are further compacted, oriented, and degraded so that the volume of voids in the aggregate decreases and there is less space for the asphalt (20). Although greater density of a bituminous mixture is beneficial in retarding deterioration due to hardening of the asphalt through weathering and stripping of the asphalt from the aggregate by the action of water, greater density is detrimental when

combined with an excessive amount of asphalt (5).

Present design procedures (21) require that the test specimen be compacted by a static, impact, or kneading type load. Procedures using impact to form specimens have not been successful in predicting ultimate density in pavements subjected to heavy channelized traffic (4). McRae (4) writes, "Investigations have shown that increasing the number of impact blows in the laboratory to attain the high densities required is infeasible if, indeed, it is even possible to attain these densities by this method."

With regard to the mechanical kneading compactor, currently used in the Hveem design procedure, Hannan (10) writes, "Using the current compaction procedure, this machine will produce excessive aggregate fracture in very open-graded mixtures, and for this reason does not simulate the true field compaction of such a mix." Gaudette (7) states, "The kneading compactor is recognized as one of the most reliable methods of compaction now in common use; however, the point to be emphasized is that although it simulates field compaction to a higher degree than earlier types of compaction used in the laboratory, there is a need to improve the compaction technique to reproduce the field condition better."

One of the principal differences between present design procedures for specimen formation and in-service pavement compaction lies in the method of application of load. Moavenzadeh writes (22),

Present practice in preparing laboratory specimens is based principally upon the concept of equal density with most of the methods incorporating some material agitation varying in some degree from direct static loading. Equal density without regard to orientation and degradation of particles cannot produce representative specimens, and unfortunately there is no way to measure the structure of specimens quantitatively in the laboratory.

Nevitt (23) considers the horizontal forces due to the movement of the tire as the main cause of differences between field and laboratory compaction. On the highway the loads are not produced by impact but are moving loads of relatively low intensity and high frequency. Also side support in the road is very different from that found in most laboratory compaction procedures.

Endersby and Vallergera in describing compaction from the stability consideration write (6):

Under the principle that the arrangement having the greater number of surface contacts as compared with point contacts will be stable in the sense of resisting further compaction, the more pushing around the particles get, the more likely it is that they will reach such a condition.

It seems clear from this that the most dependable way of getting a realistic specimen would be to roll a fair sized sample of road thickness and core it; but, it also seems clear that comparatively few laboratories could use this method for anything but research, and not many even for that, on a practical scale.

Development of the gyratory shear method of compaction led to a closer approximation of the in-service pavement condition. Philippi (26) describes an experiment by the Texas Highway Department in which nine laboratory compactors were evaluated by observing specimen characteristics and comparing them to pavement samples. He states:

The basis of comparison was the ability of the machine to produce a specimen whose density and degradation characteristics approached as nearly as possible those of satisfactory asphaltic concrete pavement in service from about four months to four years.

The data indicate that machine nine (gyratory shear) is to be preferred to the laboratory asphalt press in use in 1939 for producing a laboratory specimen whose characteristics simulate those of asphaltic concrete pavement in service.

Several references describe the Texas method of gyratory shear compaction (24) (26) (28).

To develop improved procedures for the design and control of hot-mix bituminous pavements the Waterways Experiment Station built the gyratory testing machine based on the compaction method used by the Texas Highway Department (24). The gyratory machine was used extensively in correlatory work with pavements subjected to high contact pressures (18) (19). The gyratory testing machine is described (4) as:

...a laboratory compaction and testing device believed capable of: (a) producing the high densities that develop under channelized traffic of heavy wheel loads; (b) producing specimens with stress-strain characteristics similar to those of actual pavement samples of equal density and bitumen content; (c) predicting the number of load applications a paving mixture can withstand before failure; (d) predicting the design bitumen content independently of voids criteria; and (e) providing a more positive and faster plant-control test.

Extensive laboratory and field tests proved the principle of the gyratory testing machine to be sound and its predictions to be more accurate than those of other previously established methods.

The Ohio Department of Highways has recently developed a gyratory testing machine for use in density control in bituminous paving projects (14).

For any laboratory design or test to be meaningful it must be correlated with behavior or performance in the field. It is recognized that in the area of bituminous mix design there are often gaps between laboratory designs and field performance.. Schmidt (30) lists some of the disadvantages involved in field testing which may be the cause for paucity of information in this area:

1. The cost may be prohibitive because of the size or number of tests that must be made to give significant answers.

2. It may be impossible to cope with the uncontrollable or unknown variables.

3. Most field tests should be successful: failures are not good for public relations.

4. Field testing is slow and the rate of progress may not be fast enough.

The following discussion attempts to show some of the characteristics of bituminous mixtures that have been studied in field tests. These results might be correlated with the results of a laboratory-based investigation. However, it should be noted that generally highway pavements are not homogeneous with depth but contain larger aggregate in the binder and base courses. For this reason laboratory determinations of stability or density for a particular layer may be inaccurate or unreliable as related to the field condition.

During its service life a bituminous pavement densifies. McRae (4) presents data from full-scale field tests on airport runways to substantiate this. From a field study at Wood River, Illinois, Metcalf (20) reports, "Extent of densification can be related directly to the opportunity a mix has to densify."

In a study of density effects on the repeated-load strength properties of bituminous concrete Dennis (3) hypothesizes, "Since rutting is usually accompanied by change in density and amount of voids filled with asphalt, there should be a relationship between rutting and stability." Gaudette (7) confirmed this in his work involving field sampling of Indiana pavements. He found that Hveem stability values varied widely with transverse and longitudinal location but concluded, "...the Hveem stability results do show some correlation with pavement performance for most cases..."

Although particle orientation is recognized to take place in pavements under traffic, considerations of density in laboratory design do not include any quantitative measure of particle orientation. Gaudette (7) in a study applying the kneading compactor and Hveem stabilometer to bituminous

concrete design in Indiana writes:

Cut sections of field and laboratory compacted specimens from this study have shown that the kneading compactor does not produce particle orientation of the same type as produced by construction equipment and traffic in the pavement. In the pavement the particles arrange themselves in a position with the long axis horizontal but the kneading compactor produces a random particle arrangement.

McRae (19) states:

It has also been long recognized that the stabilities obtained on laboratory specimens compacted by impact are higher than the stabilities on actual pavement cores of equivalent density and bitumen content which seems to indicate a difference in structure or aggregate particle arrangement and distribution.

Not much information is available concerning the variation of density with thickness of bituminous surface layers. Soils investigations (32) have shown that steel-wheel rollers produce the greatest density in a zone close to the roller surface. The California design procedure (27) utilizes the kneading compactor which attempts to reproduce degradation and kneading effects on the surface similar to those that might occur under traffic. Schmidt et al. (31) present data to show that for excessive compaction with steel-wheel rollers pavement density increases with depth from the pavement surface.

Compaction has been defined as (13) "...the act of artificially increasing the unit weight of the soil by manipulation in the form of pressing or ramming or vibrating the soil particles into a closer state of contact. During compaction, air is expelled. Both air and water may be expelled from pervious granular materials as the porosity is reduced by compaction." Generally it is agreed that compaction is the best way to increase the strength of granular soils. For bituminous mixtures it has been shown that compaction increases strength as long as the mix does not contain

excessive quantities of asphalt. When the voids in a mix are filled with asphalt any applied load will create pore pressures in the asphalt and failure will ensue. McLaughlin and Goetz (17) state, "...the strength or stability it (an asphalt paving mixture) exhibits in service is a function not only of its composition and state of compaction but also of the manner in which it is used."

McRae (4) and Endersby and Vallergera (6) present data that show type of compaction is important to the strength that may be expected. Generally field compaction is carried out by either steel-wheel or rubber-tire rollers or a combination of both. Bodwell (2) lists the objectives of rubber-tire rolling as:

1. Increase density
2. Achieve more uniform density
3. Sealing minor checking of pavement surface
4. Flush fines to surface and achieve tighter surface texture

Amount of compaction may be changed by variation in number of roller passes, weight of roller, contact area, and roller diameter.

At the 1957 AAPT meeting, the compaction symposium recognized the importance of construction compaction by rolling. Land (15) states, "...proper rolling is the life of our pavement. The structures on our road, even though they have good base courses and good designed mixes, must be rolled and compacted to a density that is satisfactory for the intended purpose or we have lost a good deal of the value of the asphalt pavement."

For granular materials maximum strength is usually obtained close to the maximum unit weight. McRae (19) comments on preliminary work done with the gyratory testing machine:

We build test sections at the Experiment Station and in a

given test we may vary the bitumen in panels from lean to rich and invariably the one we select as being right is in the vicinity of the peak of that unit weight curve. The physical phenomenon here might be described somewhat as follows: Starting with a lean mix, as you increase the bitumen content, you increase the lubricating effect and your density increases until you reach a peak. If you go beyond that, the bitumen begins to displace aggregate and you get a decrease in density and you have a plastic condition. That is a physical phenomenon that happens every time, regardless of type of aggregate or gradation of aggregate.

From soil mechanics considerations, compaction by rolling is effective in densification until the bearing capacity of the compacted layer is exceeded. Some highway departments control density by specifying the number and weight of rollers that must be available to compact a certain tonnage of bituminous material; some states specify that initial compaction achieve some percentage of a standard unit weight. The Ohio Department of Highways (14) has found that amount of initial compaction is critical to pavement life in late season paving operations where traffic compaction is not sufficient to seal the mix effectively against the intrusion of water and ice. Initial compaction must also leave the pavement with sufficient strength to withstand the high contact pressures of truck tires without detrimental movement.

The problem of initial compaction is one of providing adequate strength for the in-service traffic conditions. All four of the current widely-used design procedures use a different test to predict the strength suitability of a bituminous mixture (21). Endersby (11) at the initial meeting of the Triaxial Institute reports:

At the present time a number of methods exist among triaxial tests, such as the Hveem stabilometer and the Asphalt Institute methods; among other types, the Hubbard-Field, the Marshall, various shear tests, and bearing tests such as California Bearing Power. The use of most of these has been based upon empirical correlations with road work; to date it is difficult to coordinate basic conceptions of users or results of different methods, and

especially difficult to render results in commonly accepted engineering units, in such manner that the results of tests can be interpreted scientifically as well as practically. In addition, there is a continuing development of new tests, likewise empirically based, which tends to confuse the field still more. It is thought that the composition of the present group is well adapted to scientific analysis of tests....as well as fitted to work out methods practically usable to engineers in the field. The members agreed that triaxial methods were the most promising.

Triaxial testing methods are subdivided into rational and irrational tests on the basis of whether or not they are subject to a theoretical stress analysis. Goetz and Schaub (9) summarize:

Though it is felt by the authors that the triaxial method of test offers the greatest potential for a rational method of mix design, this should not be construed to mean that the method is without disadvantages. Some of the chief objections to the use of the method arise from the cost and relative complexity of the necessary equipment. In addition, the size of specimens required for the rational testing of coarse-aggregate mixtures and the number of specimens needed for a test series are considered by some as discouraging to the adoption of the method for routine testing....The analysis of triaxial data for bituminous mixtures is often complicated by a curved envelope of failure for which there is no well-defined or proven explanation. In addition, although the triaxial compression test may be performed in a strictly rational manner, namely under known conditions of stress, lack of knowledge concerning stress conditions in a pavement layer limits the application of triaxial data to empirical procedures.

The Hveem stabilometer has been found, by pavement performance correlations, to be a satisfactory tool for the measurement of pavement stability. Hveem and Davis (11) believe that materials with varying stabilities would not undergo any marked difference in relative classification whether tested in the stabilometer or in a rational triaxial apparatus. The stabilometer is described by Hveem and Davis (11):

This apparatus was developed primarily to satisfy practical considerations, and the original purpose was to develop an instrument that could be used for routine testing in a large highway laboratory. Theoretical considerations were largely subordinated to such requirements as rapid testing schedules and the need for rugged, durable equipment that could be easily

maintained in adjustment; the height of the specimen was selected to correspond to the typical thickness of bituminous surfacing commonly used in highway work; economy of material and fabrication cost were also considerations.

Although the stabilometer procedure is empirical it has been found to have good correlation with field performance and to provide a test that is relatively fast and easy to perform and hence applicable to testing adequately a large number of specimens in a short time. Numerous references describe the stabilometer and method of test (7) (10) (12) (21).

PURPOSE AND SCOPE

This study was undertaken to investigate the variation in Hveem stability of specimens formed by the gyratory shear method of compaction under conditions thought to be similar to those that occur under the influence of construction equipment and traffic. It was also expected that evaluations of the gyratory machine as a testing machine and a traffic simulator might be made in this way.

Attempts were also made to show the relationships between strength and density for specimens compacted by gyratory and kneading action. The Hveem stability index was used as a measure of the stability of the specimens. Because of time limitations most of the testing was done using the fixed upper roller.

The factors investigated in the compaction study are as follows:

- 1) Pressure exerted by the loading ram. The pressure exerted by the loading ram represents the effect of various tire contact pressures. With the gyratory testing machine these pressures may be varied to simulate the pressure condition imposed upon the prototype pavement under service.

- 2) Number of revolutions. This variable makes the gyratory machine adaptive to the traffic coverage effects that bituminous pavements must sustain. It was thought that the tests would indicate, with the exception of weathering effects, the life of the pavement under traffic.

In the course of the investigation two gradations were used—one a Fuller's maximum density gradation combined from the sieve sizes

currently composing Indiana type B surface and one a gradation proposed for high stability by Lawton (16) of the Indiana State Highway Commission.

Several asphalt contents were used in the investigation of specimen stability. Asphalt content was studied with the fixed upper roller using a constant initial compactive effort.

The angle of gyration was varied only by using the two roller types--fixed and air-filled. For the fixed roller a 1° angle of gyration was used throughout the test.

MATERIALS

The bituminous mixtures used for this study were selected to approximate those currently used by the Indiana State Highway Commission in their type B surface. It was thought that the denseness of the mixes selected would make them applicable to testing in both the gyratory machine and the Hveem stabilometer without special modification of standard test procedures. A description of the materials used in the research follows.

Mineral Aggregates

The types of aggregates used and the sources from which they were obtained are as follows:

1. Limestone	Greencastle, Indiana
2. Dune sand	Monon, Indiana
3. Natural sand	West Lafayette, Indiana
4. Limestone filler	Greencastle, Indiana

St. Genevieve limestone was obtained from deposits of the Mississippian period in west central Indiana near Greencastle. The dune sand was obtained from a gravel terrace along the Wabash river in West Lafayette, Indiana. The limestone and natural sand were obtained from commercial sources, but the dune sand was not. The filler material used was a commercially-produced filler crushed from Greencastle limestone.

Aggregate materials were tested for specific gravity and absorption according to ASTM methods C 127 and C 128. The results of these tests are shown in Table 1.

TABLE 1

RESULTS OF TESTS ON AGGREGATES

<u>Size</u>	<u>Material</u>	<u>Bulk Specific Gravity*</u>	<u>Apparent Specific Gravity*</u>	<u>% Absorption</u>
1/2"-3/8"	Limestone	2.63	2.68	1.10
3/8"-#4	Limestone	2.67	2.71	0.90
#4-#6	Limestone	2.63	2.71	1.74
#6-#8	Limestone	2.62	2.70	1.94
#8-#16	Natural Sand	2.59	2.72	2.77
#16-#50	Natural Sand	2.60	2.70	2.45
#50-#100	Natural Sand	2.63	2.70	2.63
#100-#200	Dune Sand	2.59	2.65	1.27
Passing #200	Limestone	2.71	--	--

* - average of three determinations

The commercially produced and washed aggregates, after being brought to the laboratory, were sieved into the required sizes and then washed again before storage prior to blending.

Gradations

The two gradations used in this study are shown in Figure 1. The sieve size fractions of the aggregates used, listed in Table 2, corresponded to the sizes specified by the Indiana State Highway Commission for Hot Asphaltic Concrete Surface - Type B. The Fuller's maximum density gradation for these sizes was calculated from the Fuller and Thompson empirical formula:

$$P_i = P_o \left(\frac{D_i}{D_o} \right)^{\frac{1}{2}}$$

where:

P_i = percent smaller than D_i

P_o = percent smaller than D_o

D_o = maximum particle size in gradation

The gradation D material was suggested for inclusion in the State of Indiana Standard Specifications on the basis of high stability (16).

Asphalt

A 60-70 penetration grade asphalt was used in this study. This is the penetration grade currently used by the State of Indiana for hot asphaltic concrete. Results of tests on this asphalt are presented in Table 3.

FIG.1 AGGREGATE GRADATION CURVES

TABLE 2

SIEVE-SIZE FRACTIONS USED IN GRADATIONS

U. S. Standard Sieve No.	Size of Opening in Microns
1/2" - 3/8"	12700 - 9520
3/8" - #4	9520 - 4760
#4 - #6	4760 - 3360
#6 - #8	3360 - 2380
#8 - #16	2380 - 1190
#16 - #50	1190 - 297
#50 - #100	297 - 149
#100 - #200	149 - 74
Passing #200	74-

TABLE 3
RESULTS OF TESTS ON ASPHALT CEMENT

Specific Gravity @ 77°F	1.036
Softening Point, Ring and Ball, °F	124
Ductility at 77°F, 5 cm/min, cm.	200 +
Penetration, 100 grams, 5 sec. 77°F	66
Penetration, 200 grams, 60 sec., 32°F	17
Loss on Heating, 50 grams, 5 hr., 325°F, percent	0.01
Penetration of Residue, percent of original	89
Flash Point, Cleveland Open Cup, °F	595
Solubility in CCl ₄ , percent	99.84

PROCEDURES AND EQUIPMENT

This section describes all phases of the study connected with the fabrication and testing of the bituminous specimens. Procedures and equipment for the following operations are described:

Batching and mixing

Compaction

Stability measurement

Specific gravity measurement

Unit weight gradient

Batching and Mixing

Aggregates separated into component sieve-size fractions were batched according to the blend formula. Batches of 1100 grams each were used throughout the course of the research and the batching was accomplished with cold dried aggregates using a Toledo scale sensitive to one gram.

Prior to mixing with asphalt, the aggregate batches were heated to $325 \pm 5^{\circ}\text{F}$ in a Peerless gas oven. The asphalt was heated separately to $325 \pm 5^{\circ}\text{F}$. Mixing bowl, paddle, and other utensils were also heated to approximately 325°F to prevent excessive heat loss during mixing. The hot aggregate was placed in the heated mixing bowl, and then the mixing bowl was placed on the scale and the specified percentage (by wt. of dry aggregate) of heated asphalt was added. The direct-reading pan of the scale permitted control of the amount of asphalt added to the nearest

gram. The mixing was accomplished with a Hobart (Model A-200) electric mixer modified with a special mixing paddle and a scraper. Mixing was completed in two minutes.

After mixing was completed the batch was transferred to an 11" x 7" x 1½" pan and placed in a Hotpack (Model 1412) oven provided with forced draft air circulation. The oven air temperature was maintained at $140 \pm 5^{\circ}\text{F}$ and batches were cured for a fifteen-hour period. After curing was complete the batch was again placed in the Peerless gas oven and reheated to $230 \pm 5^{\circ}\text{F}$. The batch was then ready for initial compaction.

Compaction

Two types of compaction were used in this study: kneading compaction and gyratory compaction.

Kneading compaction was performed with the California kneading compactor using the compaction procedure outlined by the Asphalt Institute design manual (22). Tamping blows of 250 and 500 psi were used. After compaction in the kneading compactor the specimens were subjected to a 1000 psi leveling load at a loading rate of 0.05" per minute in a Riehle universal testing machine.

After application of the leveling load the specimen was removed from the mold and placed in the 140°F controlled-temperature oven for at least one and one-half hours prior to testing in the Hveem stabilometer.

The gyratory compaction was accomplished using the gyratory testing machine (Model 4C) shown in Figure 2. The gyratory testing machine was developed by the Waterways Experiment Station, Vicksburg, Mississippi, and is based on a compaction technique devised by the Texas Highway Department.

FIG. 2 GYRATORY TESTING MACHINE

The gyratory testing machine is a mechanized testing machine similar in principle to the manually-operated Texas compaction apparatus and compacts a specimen by exerting 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 as two rollers that move on either side of the chuck flange revolve. The upper roller is adjustable and permits the chuck flange to be rotated or pitched about its vertical axis.

Most of the compaction in the testing was accomplished using a fixed upper roller set for a constant angle. The machine as operated with this roller produced a kneading action of the fixed-deformation type. A smaller number of tests were performed on specimens compacted by the machine using an air-filled upper roller. The air-filled upper roller permitted a fixed-stress variable deformation kneading action. Figure 3 shows a cross section of the compacting mechanism.

Although the pitch of the flange on a line connecting the rollers (which act as point loads 180° apart) is fixed, the flange can still rotate about the line between these two points, and by rotation about this line the mold chuck can develop gyratory angles in excess of the angle made by the line between the rollers.

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 the properties of the specimen, the larger will be the gyratory angle and the wider will be the gyrograph.

The compactive effort for this study was varied in three ways: by changing the ram pressure, the number of gyrations, and the type of

UPPER ROLLER
(OIL FILLED CHAMBER)

UPPER ROLLER
(AIR FILLED CHAMBER)

FIG. 3 SCHEMATIC SIDE VIEW OF SECTION
THROUGH GYRATING MECHANISM
(AFTER CORPS OF ENGINEERS)

Key to Details of Figure 3

- 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

upper roller. For fixed-roller compaction an angle of gyration of 1° was used.

Initial compaction was carried out in all cases with the fixed upper roller and a specimen temperature of $225 \pm 5^\circ\text{F}$. Secondary compaction was effected on specimens which had undergone the initial compaction phase and was carried out at a temperature of $140 \pm 5^\circ\text{F}$. The numbers of revolutions used in the initial compaction phase were 10 and 20. Secondary numbers of revolutions were generally 30, 60, 90, and 400, and a few tests were carried further to failure as indicated by the widening of the gyrograph.

Ram pressures used were 50, 100, and 150 psi. The conditions of the test were chosen both to simulate compaction in the field by construction equipment and by traffic and to effect significant differences, as measured by statistical tests, in Hveem stability measurements.

After completion of compaction in the gyratory testing machine, specimens were tested in the Hveem stabilometer, and unit weight determinations were made.

Stability Measurement

The Hveem stabilometer was used to obtain a measure of the strength of the bituminous specimen after it had been compacted. Prior to testing in the stabilometer the specimens were placed in the 140°F forced-draft oven for a minimum period of one and one-half hours. The complete procedure for testing specimens in the Hveem stabilometer is described in the Asphalt Institute's manual, Mix Design Methods for Hot-Mix Asphalt Paving (21).

The stabilometer test is essentially a closed-system triaxial test that operates on a specimen with H/D ratio ≤ 1 . Although the stabilometer

test is irrational its ease of operation and the abundance of correlation data between test results and pavement performance made the stabilometer a suitable device for measuring specimen strength in this study.

Specific Gravity Measurement

Two types of specific gravity measurements were used in the testing of mixture specimens: bulk specific gravity and Rice specific gravity. Upon completion of compaction, specimens were cooled to room temperature, wiped free of any loose aggregate, and weighed in air. The specimens were then submerged in water for a 24-hour absorption period. After the 24-hour period of absorption specimens were weighed in water and saturated-surface-dry in air. For the bulk specific gravity determinations the following formula was used:

$$S.G. \text{ bulk} = \frac{W_a}{W_{ssd} - W_w}$$

where:

W_a = weight of specimen in air

W_{ssd} = saturated-surface-dry weight in air

W_w = weight of saturated specimen in water

Rice specific gravity was obtained for those specimens for which voids were to be computed. The Rice specific gravity determination is a vacuum saturation procedure used for determining the maximum specific gravity of bituminous paving mixtures. Details of the procedure followed in determining the Rice specific gravity may be found in ASTM Special Technical Publication No. 191 (29).

Unit Weight Gradient

Uniformity of density with specimen height was studied by cutting

the specimen in half with a masonry saw. Because the sawing operation wetted the specimen halves, they were washed free of dust and placed in water for the 24-hour absorption period. W_w and W_{ssd} values were recorded and the specimen halves were then placed on absorbent paper and air-dried at room temperature with the aid of a fan for 24 hours. The weight in air was then recorded and the specific gravity computed as described in the preceding section.

RESULTS

In this section test results from this study are presented together with discussion and evaluation. Data not presented in this section will be found in APPENDIX A. For clarity of presentation graphical illustrations of trends indicated by data are used whenever possible. Statistical tests and statistical computations used in evaluation of data are presented in APPENDIX B and APPENDIX C respectively. Results of statistical tests pertinent to the discussion of results are presented in this section.

The following topics are considered under the presentation and discussion of results:

- Influence of stabilometer test on compacted specimens

- Fixed-roller operation

- Initial compaction

- Secondary compaction

- Gradation

- Design procedures

- Design for dense-graded mixes

- Design for open-graded mixes

- Air-filled roller operation

- Variation of unit weight with specimen height

- Particle orientation

Influence of Stabilometer Test on Compacted Specimens

It is recognized that specimens tested in the Hveem stabilometer

are deformed in the course of testing. To evaluate whether or not this deformation had an effect on the unit weight of specimens, it was necessary to perform a statistical test. Ten specimens were compacted using 100 psi ram pressure, 10 revolutions, and a 1° angle of gyration in the gyratory testing machine. Bulk unit weights of these specimens were determined both after compaction and after testing in the stabilometer. A statistical test of differences in bulk unit weight before and after testing in the Hveem stabilometer showed that the stabilometer caused a significant change in bulk unit weight. The stabilometer test increased the bulk unit weight of these specimens by approximately 1.7 pcf. The bulk unit weights determined before and after the stabilometer test are shown in Table 4. Statistical analysis of these data is presented in APPENDIX C.

Because the compactive effort imposed on these ten specimens was low compared to that used in later testing, and because the differences in bulk unit weight appeared to be uniform, no corrections for unit weight change were made in subsequent testing. This was justified by considering that increased compaction would have increased stability and resistance to deformation. It should be noted that this increase in bulk unit weight would tend to give a low estimate of % voids in the mix. The following sample calculation and sketch will illustrate this.

$$\% \text{ Voids} = \frac{D - d}{D} \times 100 \quad \text{where:}$$

D = maximum unit weight

d = unit weight after some level of compaction

For $D = 152.0$ pcf

$d_{\text{before stabilometer test}} = 146.0$ pcf = d_b

$d_{\text{after stabilometer test}} = 147.7$ pcf = d_a

} hypothetical data

TABLE 4
COMPARISON OF BULK UNIT WEIGHT BEFORE AND AFTER
STABILOMETER TEST

(1) BULK UNIT WEIGHT - PCF		(2)	BULK UNIT WEIGHT - PCF
BEFORE STABILOMETER TEST	AFTER STABILOMETER TEST		(2) - (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	<u>1.9</u>
			10.7

Mean difference = $\frac{10.7}{10} = 1.07$ pcf

$$\% \text{ Voids}_{\text{before}} = \frac{152.0 - 146.0}{152.0} = 4.0\%$$

$$\% \text{ Voids}_{\text{after}} = \frac{152.0 - 147.7}{152.0} = 2.9\%$$

Fixed-Roller Operation

The largest category of testing in this research involved stability measurement of specimens compacted using fixed-roller operation in the gyratory testing machine. Variables for this series of tests included two aggregate gradations, three initial compaction pressures, two initial compaction revolutions, four secondary compaction pressures, and four secondary compaction revolutions.

Pressures were chosen to be representative of the range of contact pressures that might be expected from construction equipment and traffic. Tire contact pressures of ordinary compacting equipment and heavy vehicles may be expected to lie between 50-150 psi (1). The initial number of

revolutions (10 or 20) was chosen to bracket the range of roller passes a bituminous layer might receive from construction compaction equipment.

Two gradations--one dense and one open--were used to study effects of aggregate gradation on specimen stability. These gradations are presented under the section entitled MATERIALS AND TESTS.

The sequence of compaction involved simulated construction compaction at either 10 or 20 initial revolutions and 50, 100, or 150 psi initial pressure. This initial compaction was carried out at 225°F and utilized fixed-roller operation and a 1° angle of gyration in all tests. Simulated traffic or secondary compaction involved additional revolutions (30, 60, 90, 400) and secondary pressures of 50, 100, or 150 psi. Secondary compaction was carried out at 140°F. Subsequent to secondary compaction, specimens were tested in the Hveem stabilometer. For the first series of tests using fixed-roller compaction, asphalt content was not varied. One hundred ninety-two specimens containing 4% asphalt were used for this series of tests. Asphalt content for the entire research was specified as percent by weight of the dry aggregate.

To study the variation in stability caused by the factors involved in the compaction process, two analysis of variance tests were used. The first of these was a three-way classification (fixed effects model) with a single case in each class. This test is described in APPENDIX B. Four of these analyses were required to analyze data common to each of two gradations and two values of initial revolutions. The three factors and their levels used in this three-way classification are as follows:

<u>Factor</u>	<u>Levels of Factor</u>
Secondary pressure, psi	0, 50, 100, 150
Secondary revolutions	30, 60, 90
Initial pressure, psi	50, 100, 150

Results of this analysis of variance are presented in Tables 5, 6, 7 and 8. In all four analyses the three main factors as well as one or more combinations of the main factors were indicated responsible for a significant change in stability. This is represented in Tables 5 through 8 by the Reject H_0 indicated under the column headed "Decision." The presence of a significant combination of main factors--a significant interaction--indicated that the joint effect of the factors involved exceeded the sum of the individual effects. To make statements about individual effects where interaction occurred required the use of the Newman-Keuls sequential range test. This test allowed identification of significant changes in Hveem stability at various levels of the main factors studied. The results of the Newman-Keuls analyses for the interacting factors are shown in Figures 4, 5, 6, 7 and 8. The solid lines connecting the Hveem stability values on these figures indicate that a significant difference in stability is caused by the increment of the factor measured along the abscissa. A description of the Newman-Keuls test and the complete computations for one interaction are presented in APPENDIX C.

Significant changes in Hveem stability were measured by the analysis of variance and Newman-Keuls test. Because of time limitations only one replication of each compactive effort was made.

A ranking of the relative importance of the three main factors in effecting changes in stability can be obtained from the size of the mean squares in Tables 5, 6, 7 and 8. Generally it may be said that for the main factor increments chosen, the factors most important in increasing stability values are in order of importance: secondary pressures, initial pressure, and secondary revolutions.

TABLE 5

ANALYSIS OF VARIANCE (FIXED EFFECTS MODEL)

FULLER'S MAXIMUM DENSITY GRADATION
10 REVOLUTION INITIAL COMPACTIONLEVELS OF
FACTORFACTORS

A - Secondary Revolutions

3

B - Secondary Pressure

4

C - Initial Pressure

3

 H_0 : Stability not affected by Factor ($\alpha = 0.05$).

FACTOR	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	VARIANCE RATIO	F _{0.05}	DECISION
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	43.74	4.06

FIG. 4 RESULTS OF NEWMAN-KEULS ANALYSIS
 FOR SECONDARY PRESSURE-INITIAL PRESSURE
 INTERACTION
 FULLER'S MAXIMUM DENSITY GRADATION, 10 REVOLUTION
 INITIAL COMPACTION, 4 % ASPHALT

TABLE 6

ANALYSIS OF VARIANCE (FIXED EFFECTS MODEL)

FULLER'S MAXIMUM DENSITY GRADATION
20 REVOLUTION INITIAL COMPACTIONLEVELS OF
FACTORFACTORS

A - Secondary Revolutions

B - Secondary Pressure

C - Initial Pressure

 H_0 : Stability not affected by Factor ($\alpha = 0.05$).

FACTOR	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	VARIANCE RATIO	$F_{0.05}$	DECISION
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	23.95	2.41

FIG. 5 RESULTS OF NEWMAN-KEULS ANALYSIS
 FOR SECONDARY PRESSURE-INITIAL PRESSURE
 INTERACTION
 FULLER'S MAXIMUM DENSITY GRADATION, 20 REVOLUTION
 INITIAL COMPACTION 4 % ASPHALT

TABLE 7

ANALYSIS OF VARIANCE (FIXED EFFECTS MODEL)

GRADATION D
10 REVOLUTION INITIAL COMPACTIONLEVELS OF
FACTORFACTORS

A - Secondary Revolutions

B - Secondary Pressure

C - Initial Pressure

 H_0 : Stability not affected by Factor ($\alpha = 0.05$)

FACTOR	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	VARIANCE RATIO	F _{0.05}	DECISION
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

FIG. 6 RESULTS OF NEWMAN-KEULS ANALYSIS FOR SECONDARY PRESSURE-SECONDARY REVOLUTION INTERACTION

GRADATION D, 10 REVOLUTION INITIAL COMPACTION, 4 % ASPHALT

TABLE 8

ANALYSIS OF VARIANCE (FIXED EFFECTS MODEL)

GRADATION D
20 REVOLUTION INITIAL COMPACTION

LEVELS OF
FACTOR

FACTORS

A - Secondary Revolutions

3

B - Secondary Pressure

4

C - Initial Pressure

3

 H_0 : Stability not affected by Factor ($\alpha = 0.05$).

FACTOR	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	VARIANCE RATIO	$F_{0.05}$	DECISION
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

FIG. 7 RESULTS OF NEWMAN-KEULS ANALYSIS
FOR SECONDARY PRESSURE-INITIAL PRESSURE
INTERACTION

GRADATION D, 20 REVOLUTION INITIAL COMPACTION, 4 %
ASPHALT

FIG. 8 RESULTS OF NEWMAN-KEULS ANALYSIS
FOR SECONDARY PRESSURE-SECONDARY
REVOLUTION INTERACTION
GRADATION D, 20 REVOLUTION INITIAL COMPACTION, 4 %
ASPHALT

A second statistical test was used to evaluate the effect of all five main variable factors on specimen stability. This test was a five-way analysis of variance (fixed effects model) and is described in statistical reference 3S. It included the following factors and levels of factors:

<u>Factor</u>	<u>Levels of Factor</u>
A - Secondary revolutions	30, 60, 90, 400
B - Secondary pressure, psi	0, 50, 100, 150
C - Initial pressure, psi	50, 100, 150
D - Initial revolutions	10, 20
D - Gradation	Fuller's maximum density and gradation D

This analysis differed from the three-way analysis of variance in that it included factors of initial revolutions and gradations as well as another level of secondary revolutions. Results of this analysis of variance are presented in Table 9. 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 more comprehensive analysis of variance, the factors most significant in changing specimen stability were, in order of importance: secondary revolutions, initial pressure, secondary pressure, initial revolutions, and gradation.

It should be noted that 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 9 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. These effects would be obtained from a computer analysis which would be

TABLE 9

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

H_0 : Stability not affected by factor ($\alpha = 0.05$)

FACTORS	MEAN SUM OF SQUARES	DEGREES OF FREEDOM	F	$F_{0.05}$	DECISION	ESTIMATE OF σ^2 FACTOR
A - Secondary Revolutions	387.8	3	129.3	2.76	Reject H_0	8.0
B - Secondary Pressures	279.2	3	93.1	2.76	Reject H_0	5.7
C - Initial Pressures	475.8	2	237.9	3.15	Reject H_0	7.4
D - Initial Revolutions	324.7	1	234.7	4.00	Reject H_0	2.4
E - Gradations	80.2	1	80.2	4.00	Reject H_0	0.8
AB	43.9	9	4.9	2.04	Reject H_0	3.5
AC	4.1	6	0.7	2.25	Accept H_0	
AD	79.1	3	26.4	2.76	Reject H_0	3.1
AE	81.5	3	27.2	2.76	Reject H_0	3.2
BC	30.2	6	5.0	2.25	Reject H_0	1.2
BD	26.0	3	8.7	2.76	Reject H_0	0.9
BE	156.2	3	52.7	2.76	Reject H_0	6.3
CD	36.8	2	18.4	3.15	Reject H_0	1.0
CE	21.3	2	10.7	3.15	Reject H_0	0.5
DE	32.6	1	32.6	4.00	Reject H_0	0.6
ABC	1.2	18	0.1	1.80	Accept H_0	
ABD	10.3	9	1.1	2.04	Reject H_0	1.0
ABE	27.9	9	3.1	2.04	Reject H_0	3.9
ACD	0.0	6	0.0	2.25	Accept H_0	
ACE	2.6	6	0.4	2.25	Accept H_0	
ADE	9.4	3	3.1	2.76	Accept H_0	
BCD	0.0	3	0.0	2.25	Accept H_0	
BCE	8.3	6	1.4	2.25	Accept H_0	
BDE	0.7	6	1.4	2.25	Accept H_0	
CDE	1.0	3	0.5	3.15	Accept H_0	
Error	4.2	75				
Total		191				

necessary for large-scale correlation between laboratory and field results.

Subsequent discussion in this section describes particular results caused by fixed-roller operation compaction.

Initial Compaction

The effect of initial compaction pressure on initial stability of specimens is shown in the plot of Hveem stability vs initial pressure in Figure 9. In all cases increasing the initial compaction pressure increased initial stability. Generally the increase in pressure from 50 psi to 100 psi increased stability somewhat more than the increase in pressure from 100 psi to 150 psi. Each point on this plot represents the average of three stability determinations. Uniformity of stability after initial compaction was evident in all cases. Deviation from the mean stability value shown on the graph was of the order of $\pm 1\frac{1}{2}$ stability units or less. Data are presented in APPENDIX A. The initial stability measurements shown in the top graph in Figure 9 were all lower than the 35 value specified for adequate heavy duty surfaces in the Hveem design procedure. This indicates that if the initial compaction in the gyratory testing machine is representative of construction compaction, and the mixes tested would be stable in heavy duty service, a considerable portion of specimen stability must come from secondary or traffic-imposed compaction. This occurrence has been noted in the REVIEW OF LITERATURE.

From the plot of Hveem stability vs initial revolutions shown in Figure 9 it is seen that increasing initial revolutions from 10 to 20 increased initial stability. From the slopes of the graphs it is seen that the increase in initial revolutions is most effective in increasing initial stability of specimens compacted at low pressure. Comparison of

FIG. 9 EFFECTS OF INITIAL PRESSURE AND INITIAL REVOLUTIONS ON SPECIMEN STABILITY

the two plots of Figure 9 shows that the range of stability increase produced by increasing initial revolutions from 10 to 20 is less than that obtained by increasing initial pressure from 50 psi to 150 psi.

It is recognized that the confinement and deformation characteristics in the gyratory testing machine operating with fixed-roller conditions are different from those encountered in the field under steel-wheel rollers. One difference between fixed-roller operation and field compaction may be noted in the manner in which deformation progresses. Under compaction equipment in the field, the layer of bituminous material will become more dense. Accompanying this there will be an increase in bearing capacity and lateral support so that subsequent passes with compacting equipment will cause successively smaller deformations. Compaction using the fixed-roller operation deforms the specimen by an angular amount at least equal to the gyratory angle (in this case 1°). This movement produces an accelerated progression of density and stability in the bituminous specimen.

A comparison of the estimates of σ^2_{factor} for initial compaction pressures and initial revolutions obtained from Table 9 (7.4 vs 2.4) indicates that, for the increments used in this test, compaction pressure is about three times as effective in changing stability as initial compaction revolutions. To determine whether an actual correspondence exists between revolutions in the gyratory testing machine and passes of compaction equipment would require a controlled field study of density and rolling.

Secondary Compaction

Figure 10 presents a plot of Hveem stability vs number of secondary revolutions for the Fuller gradation. In general, for the cases shown,

FIG. 10 HVEEM STABILITY VS NO. SECONDARY REVOLUTIONS
FULLER'S MAXIMUM DENSITY GRADATION, 10 REV. INITIAL COMPACTION

the higher secondary compaction pressures initially increased stability more rapidly than lower secondary pressures. Maximum stability at 100 revolutions for a constant secondary pressure in Figure 10 does not necessarily occur on the graph with the highest initial stability. For both 100 psi and 150 psi secondary compaction pressures the order of specimen stabilities is changed during the course of compaction from 10 revolutions to 100 revolutions. This indicates that stability is dependent upon revolutions as well as upon initial stability and secondary compaction pressure.

Lack of adequate stability of bituminous mixes is often reflected by rutting and flowing. The following illustration will help clarify the deformed condition of rutting and flowing pavements.

It is possible that these terms are found more distinct in definition than in practice. Because of the confinement that exists in the gyratory mold, no estimate of relative effects of secondary pressure can be made for flowing failures. However, it can be said that mixtures subject to rutting failure will also flow and shove if the failure progresses.

Figures 11 to 13 may be interpreted as indications of rutting potentials under varying secondary pressure for mixtures compacted with 20 revolutions of varying initial pressure. The semilog plots of axial deformation vs number of revolutions shown in Figures 11 to 13 record axial deformation as the difference between specimen height when only a static load was applied and specimen height after some number of revolutions. From these

FIG. 11 AXIAL DEFORMATION VS NO. REVOLUTIONS

FIG. 12 AXIAL DEFORMATION VS NO. REVOLUTIONS

FIG. 13 AXIAL DEFORMATION VS NO. REVOLUTIONS

figures it will be noted that the curves are concave downward for secondary compaction pressures greater than or equal to the initial compaction pressure. This indicates that rate and amount of axial deformation are dependent upon initial compaction pressures as well as secondary compaction pressures.

From Figure 11, secondary compaction utilizing a pressure of 50 psi for 400 revolutions on a specimen compacted with 50 psi initial pressure increased total deformation from 0.36" to 0.54", a net change of 0.18" for a 2½" high specimen. Secondary compaction of 150 psi for similar limits in Figure 11 increases total deformation from 0.38" to 0.64", a net change of 0.26". Thus, for the same initial 50 psi compaction a 150 psi secondary compaction pressure produced $0.26 - 0.18 = 0.08$ " more total axial deformation than a 50 psi secondary pressure.

Figures 11 to 13 also allow comparison of total deformation caused by different initial pressures. As an example of this, comparison may be made between axial deformation caused by 150 psi and 50 psi secondary pressures for respective initial compaction using 50 psi and 150 psi pressures. From Figure 11 (initial compaction pressure 50 psi) it was noted that the change in axial deformation caused by a secondary pressure of 150 psi was $0.64 - 0.38 = .26$ ". From Figure 13 (initial compaction pressure 50 psi) the change in axial deformation caused by 50 psi secondary pressure was $0.48 - 0.37 = 0.11$ ". The net change in deformation for this example is $0.26 - 0.11 = 0.15$ ". It would seem from these comparisons that high tire contact pressures would contribute considerably to pavement rutting in cases where initial compaction did not sufficiently densify the mix. This has been demonstrated for the more-dense mix only, but it is expected that gradation D would perform similarly.

In all cases observed in Figures 11 to 13 axial deformation increased. This shows that specimen confinement was sufficient to prevent any 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 14, 15, 16, 17 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. It will be noted from the figures that the graphs approximate straight lines for low pressures up to approximately 100 revolutions. In this range a graph of the stability vs time relationship on an arithmetic plot would be parabolic.

The upper limit of 400 revolutions was chosen arbitrarily. For gradation D (Figures 16 and 17) increasing revolutions increased stability for the entire range of revolutions. This was not the case for the Fuller gradation shown in Figures 14 and 15. Stabilities for the high secondary pressures decreased with increasing secondary revolutions, indicating that this measurement may provide a relative index of mixture resistance to loss of stability under traffic. For any conditions of secondary pressure and fixed-roller operation it would be possible to obtain the stability vs revolutions curve for any mix.

For the Fuller gradation shown in Figures 14 and 15, decreased in stability may be noted at the 400 revolution level for both 10 and 20 revolution initial compaction. In general, greater decreases in stability occurred in specimens compacted using higher secondary compaction pressures.

FIG. 14 HVEEM STABILITY VS NO. OF REVOLUTIONS
 10 REVOLUTION INITIAL COMPACTION, FULLER'S
 MAXIMUM DENSITY GRADATION, 4% ASPHALT

FIG. 15 HVEEM STABILITY VS NO. OF REVOLUTIONS
 20 REVOLUTION INITIAL COMPACTION, FULLER'S
 MAXIMUM DENSITY GRADATION, 4% ASPHALT

FIG. 16 HVEEM STABILITY VS NO. OF REVOLUTIONS
 10 REVOLUTION INITIAL COMPACTION
 GRADATION D, 4% ASPHALT

FIG. 17 HVEEM STABILITY VS NO. OF REVOLUTIONS
 20 REVOLUTION INITIAL COMPACTION
 GRADATION D, 4% ASPHALT

This result should be expected from energy considerations, i.e., because compaction is an energy-consuming process the results of compaction should be measurable in energy units.

Generally the Fuller gradation stability values increased up to 100 revolutions. At 400 revolutions marked decreases in stability occurred for both 10 and 20 revolution initial compaction. For the most part, specimens compacted initially for 20 revolutions had somewhat lower stability values after 400 revolutions than specimens compacted initially for 10 revolutions. Because the only difference between the 10 and 20 revolution 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 is responsible for the apparent difference in stability and resistance to loss in stability. No detailed attempt was made in this study to analyze the effects of compaction temperature on specimen stability; however, this result indicates some type of compaction temperature specification to be necessary to insure uniformity of compaction. It is recognized that asphalt in thin films exhibits a greater resistance to compaction at low temperatures than it does at high temperatures.

From the estimate of σ^2_{factor} (8.0 vs 5.7) presented in Table 9, it is seen that for the increments of secondary pressure and secondary revolutions chosen for this study, secondary revolutions are more important in causing stability change than secondary pressures.

Gradation

Two gradations were used in the research to determine the applicability of a gyratory design procedure to both open- and dense-graded mixes. A description of the mixes used is included in the MATERIALS AND TESTS section. Use of these gradations was justified by similarity to Indiana

State Highway Department specifications, considerations of denseness, applicability to the test equipment, and results anticipated. From Figures 14 and 15, semilog plots of Hveem stability vs number of revolutions for the Fuller gradation, it may be seen that a maximum stability was attained within 400 revolutions for most compaction pressures. Maximum stability of this gradation with 4% asphalt appeared to be greater than 35 but less than 40 Hveem stability units.

For gradation D with 4% asphalt, values of stability for 10 and 20 revolutions initial compaction are indicated in Figures 16 and 17. No maximum stability is indicated by either figure. For low compaction pressures the stabilities of the mix were generally less than 35 while for the 150 psi compaction pressures stabilities of 50 or greater were measured. The low value, 0.8, of σ^2_{factor} in Table 9 shows that gradation was the least influential main factor in changing stability values.

Design Procedures

The preceding tests were performed to study the manner in which stability values were influenced by compaction variables thought to be representative of those occurring in bituminous pavements under traffic. To determine if the gyratory testing machine had represented the stability condition adequately enough for mixture design the tests described in this section were performed.

The design of a bituminous mix essentially involves the selection of an asphalt content which is optimal for the stability requirements dictated by its use. To optimize durability it is desirable to add as much asphalt as possible without sacrificing required stability. The

purpose of the research included in the following two sections was to determine whether the gyratory testing machine is capable of indicating a valid design asphalt content for highway pavements.

Design for Dense-Graded Mixes

Typical gyrographs are presented in Figure 18. The gyrographs give an indication of the plastic properties of the specimen during compaction. A widening gyrograph indicates that the specimen is becoming more plastic. From the gyrographs obtained during the compaction of the Fuller gradation it was evident (cf. Figure 18) that the gyratory testing machine indicated that the mix reached a limit of stability within the range of compaction studied. This was also indicated by the decrease in Hveem stability shown for high secondary pressures in Figures 14 and 15. It appeared that qualitative judgment of the sensitivity of the mix could be made from the rate at which the gyrographs widened. The gyrographs showed a consistent tendency to widen at high compactive efforts. Evidence that 4% asphalt was excessive for the Fuller gradation compacted at high pressures and revolutions was evident also from the glossy and "flushed" appearance that these specimens showed after being removed from the compaction mold.

Figure 19 presents the results of voids determinations for the Fuller gradation determined from bulk specific gravity and vice maximum specific gravity. This figure presents a semilog plot of % voids vs secondary number of revolutions for 20 revolution initial compaction. Comparison of Figure 19 with Figure 15 shows that Hveem stability decrease corresponds to void contents of less than 2%. A good correspondence between % voids and widening of the gyrograph was also indicated. It should be noted that % voids shown in Figure 19 were obtained after the stability determination

20 REVOLUTION INITIAL COMPACTION

400 REVOLUTION SECONDARY COMPACTION

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FIG. 18 TYPICAL GYROGRAPHS-FIXED ROLLER OPERATION

FULLER'S MAXIMUM DENSITY GRADATION

FIG. 19 % VOIDS VS NO. OF REVOLUTIONS

and hence the % voids shown for the lower numbers of revolutions may be lower than the % voids present in the specimen in the gyratory testing machine. This difference has been noted in a previous section of RESULTS.

To relate the gyratory design technique to a standard design procedure, six specimens were prepared by the standard kneading compaction technique specified in the Hveem design procedure. Asphalt content was varied in $\frac{1}{2}\%$ increments from $3\frac{1}{2}\%$ to 6%. Figure 20 presents a plot of Hveem stability and % voids vs % asphalt. This graph indicates that 4% asphalt is the optimum asphalt content to the nearest $\frac{1}{2}\%$. The rather steep slope of the stability curve indicates that the mix is quite sensitive with respect to amount of asphalt and infers mixture sensitivity with increased compaction which is shown more completely by Figure 14 and the gyrographs in Figure 18. From this it was concluded that a design procedure for dense mixes using the gyratory testing machine was at least as good as the standard Hveem design technique with respect to specifying % asphalt. Advantages of using the gyratory design for the dense gradation included indication of the sensitivity of the mix to decrease in stability with further compaction and of the possibility for elimination of % voids determinations.

Figure 21 is a plot of unit weight and maximum unit weight as % asphalt for specimens with asphalt contents from 3.5% to 6% compacted by standard kneading compaction. It should be noted that for this gradation with asphalt contents greater than 4.5% accurate determinations of % voids is difficult. For the unit weights shown for 6% asphalt a negative % voids would be calculated. This difficulty in determination of low % voids is present in all currently-used laboratory design procedures.

FIG.20 HVEEM STABILITY AND % VOIDS
VS % ASPHALT

FULLER'S MAXIMUM DENSITY GRADATION, KNEADING
COMPACTION

FIG 21 UNIT WEIGHT AND MAXIMUM UNIT WEIGHT VS % ASPHALT

FULLER'S MAXIMUM DENSITY GRADATION, KNEADING COMPACTION

Design for 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 were compacted in the gyratory testing machine and tested in the stabilometer. Asphalt content was varied in 1% increments over the range of 4% to 7%. Data for these tests are included in APPENDIX A.

Figures 22 and 23 show semilog plots of Hveem stability vs number of revolutions for these specimens. In each case stability values increased with number of revolutions; however, stability at 400 revolutions decreased with increasing asphalt content for 150 psi secondary pressures. For all 60 gradation D specimens there was no widening of the gyrographs with increasing numbers of revolutions up to the 400 revolutions applied.

Comparison of the results presented above with results from the standard Hveem procedure was also made. Four specimens were compacted using the standard Hveem design compaction procedure. Asphalt content was also varied in 1% increments over the range of 4% to 7%. The data are presented in APPENDIX A. Figure 24 is a plot of Hveem stability and % voids vs % asphalt which can be compared to Figure 20 obtained for dense mixes. It will be noted that corresponding stability values shown in Figure 24 are much less than those indicated in Figures 22 and 23 for the gyratory-compacted specimens. No indication of a critical asphalt content was evident from either stabilometer values or widening gyrographs for specimens compacted by gyratory compaction up to 400 revolutions. Possibly higher ram pressures with this gradation would have yielded more information on a critical asphalt content, but it was thought that pressures higher than 150 psi would have been unrepresentative of normally severe pressures of construction equipment and traffic.

FIG. 22 HVEEM STABILITY VS NO. OF REVOLUTIONS
 10 REVOLUTION, 100 PSI INITIAL COMPACTION
 GRADATION D, VARYING ASPHALT CONTENT

FIG. 23 HVEEM STABILITY VS NO. OF REVOLUTIONS
10 REVOLUTION, 100 PSI INITIAL COMPACTION
GRADATION D, VARYING ASPHALT CONTENT
(CONTINUATION OF FIG. 22)

Figure 24 shows that an asphalt content of 5.5% is required to obtain the 4% voids generally desired in the Hveem design procedure. It should be noted that this mixture would not be stable according to the Hveem criteria because 5.5% asphalt would yield a stability of only 24, less than that required for heavy traffic by the Hveem criteria. Values of % voids for gyratory-compacted specimens of 6% asphalt were 3.7, 3.2, and 2.4% for secondary pressures of 50, 100, and 150 psi and 400 revolutions. From the top graph of Figure 22, it is seen that this compactive effort yields stabilities of 35 to 45. For this same range of % voids (2.4 to 3.7) Figure 24 shows stabilities from kneading compaction to be less than 30 stability units. For the same % voids stabilities for kneading-compacted specimens and gyratory-compacted specimens are markedly different.

By way of possible explanation for the difference in results obtained by kneading and gyratory compaction of the open-graded mixture, it should be noted that the high kneading foot pressures specified by the Hveem design procedure produced considerable degradation in specimen tops. This may account for the low stabilities measured for kneading-compacted specimens; although the % 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 kneading-compacted specimens. The low-void top sections could be responsible for low stability values of kneading-compacted specimens indicated by the stabilometer test. Statistical analyses of variation in unit weight with specimen height for kneading- and gyratory-compacted specimens are given later in this section. Support for this explanation is given by the fact that these analyses show an average difference of 6 pcf for the kneading-compacted specimens and only 1.7 pcf for the gyratory-compacted specimens.

FIG. 24 HVEEM STABILITY AND % VOIDS
VS % ASPHALT

GRADATION D, KNEADING COMPACTION

Figure 25 presents a plot of unit weight and maximum unit weight vs % asphalt. Comparison of Figures 25 and 21 shows that for standard kneading compaction unit weights of the gradation D specimens were 6 to 8 pcf lighter than Fuller gradation specimens.

Air-Filled Roller Operation

Tests were performed with the air-filled upper roller, but in lesser number than those using the fixed upper roller. Although the variable deformation compaction may be an important research tool, it was decided that the fixed-deformation type of compaction would be more extensively explored in this study because of time limitations.

To determine the effect of ram pressure on stability, nine specimens of gradation D, 4% asphalt were compacted initially for 10 revolutions at 50 psi using the fixed upper roller. Secondary compaction of 400 revolutions used ram pressures of 50, 100, 150 psi and air gauge pressures of 12, 25, and 50 psi. Results presented in Figure 26 show essentially constant stability for air pressures of 12 and 25 psi, but increasing stabilities for the 50 psi air pressure. Comparison of these stability values with those shown for similar compaction revolutions using the fixed upper roller (lower graph of Figure 17) shows the stabilities of the specimens compacted with variable strain compaction to be equal to those compacted using fixed-roller operation.

Figure 27 presents % voids vs secondary ram pressures for 400 secondary revolutions. It appears that only the 50 psi air gauge pressure was effective in decreasing % voids with increasing ram pressures. Compaction using the air-filled upper roller at low air gauge pressures approaches static compaction in which particle orientation is minimal.

FIG. 25 UNIT WEIGHT AND MAXIMUM UNIT WEIGHT VS % ASPHALT

GRADATION D, KNEADING COMPACTION

FIG. 26 HVEEM STABILITY VS SECONDARY RAM PRESSURE

AIR-FILLED UPPER ROLLER, 400 REVOLUTION SECONDARY COMPACTION

FIG.27 % VOIDS VS SECONDARY RAM PRESSURE

AIR-FILLED UPPER ROLLER, 400 REVOLUTION SECONDARY COMPACTION

Representative portions of the gyrographs obtained from gyratory compaction using the air-filled upper roller are presented in Figure 28. These data show the gyration permitted by the air-filled upper roller using air gauge pressures of 12, 25, and 50 psi. Eight small increments of the recorder paper represent an angle of gyration of 1° . These figures indicate that for a constant ram pressure stability is a function of the angle of gyration. It appears that densities and stabilities produced by air-filled roller compaction would be equivalent to those produced by fixed-roller compaction provided air gauge pressures were high enough.

Variation of Unit Weight With Specimen Height

Variation of unit weight with specimen height was studied by cutting compacted specimens in half and determining unit weights of specimen tops and bottoms. Statistical tests of the differences in unit weights from specimen tops and bottoms were made to determine whether a significant difference in unit weight existed.

Eighteen specimens of gradation D with 4% asphalt were compacted in the gyratory testing machine using ten revolutions of fixed-roller operation at 100 psi and a 1° angle. The eighteen specimens were divided into two groups of nine specimens each. The first group received secondary compaction up to a maximum of 90 secondary revolutions. Specific compaction conditions for each specimen are shown in Table 10. A statistical analysis of these data showed differences in bulk unit weights between specimen tops and bottoms to be insignificant. The statistical analysis used is presented in APPENDIX C.

The second group of nine specimens received 390 secondary revolutions

FIG.28 TYPICAL GYROGRAPHS AIR-FILLED ROLLER OPERATION

GRADATION D, 10 REVOLUTION, 50 PSI, 1° ANGLE INITIAL COMPACTION

TABLE 10

UNIT WEIGHT GRADIENT OF GYRATORY-COMPACTED SPECIMENS

Gradation D

10 Revolution, 100 psi, 1° Angle Initial Compaction

4% Asphalt

PSI	SECONDARY COMPACTION AT 1° ANGLE REVOLUTIONS	BULK UNIT WEIGHT - PCF		BULK UNIT WEIGHT - PCF	
		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
	none	134.2	132.3		1.9
	none	134.2	135.4		-1.2

under conditions of fixed-roller operation at the pressures shown in Table 11. A statistical analysis similar to the one described for the first group resulted in the rejection of the hypothesis that unit weights of specimen tops and bottoms were uniform. Statistical analyses for these two groups of specimens are included in APPENDIX C. The unit weights presented in Table 11 show that specimen bottoms had higher unit weights than specimen tops. In all cases gradation D was used because it was thought that the more open mixture would reflect more markedly existence of a unit weight gradient.

For secondary compaction, the fixed upper roller was replaced by the air-filled upper roller and seven specimens were compacted as shown in Table 12. A statistical analysis of the unit weight data showed specimen bottoms had significantly greater unit weights than specimen tops. No evidence of unit weight gradient was evident from visual examination of these specimens. These tests showed that the existence of a unit weight gradient in gyratory-compacted specimens was dependent upon the amount of compaction received. Where a unit weight gradient existed specimen bottoms were more dense than specimen tops.

Unit weight gradient in kneading-compacted specimens was studied by compacting six gradation D specimens in the kneading compactor using the standard Hveem design compaction procedure. Asphalt contents were varied in $\frac{1}{2}\%$ increments from 4% to 6 $\frac{1}{2}\%$. Data for these tests are given in Table 13. For all kneading-compacted specimens the unit weight of specimen tops exceeded the unit weight of specimen bottoms. The results show that the average difference in bulk unit weight was 0.0 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

TABLE 11

UNIT WEIGHT GRADIENT OF GYRATORY-COMPACTED SPECIMENS

Gradation D
10 Revolutions, 1° Angle Initial Compaction
4% Asphalt

INITIAL PRESSURE - PSI	SECONDARY PRESSURE AT 1° ANGLE 390 REVOLUTIONS - PSI	BULK UNIT WEIGHT - PCF		BULK UNIT WEIGHT - PCF FOI-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

TABLE 12
UNIT WEIGHT GRADIENT OF GYRATORY-COMPACTED SPECIMENS

Gradation D
10 Revolutions, 50 psi, 1° Angle Initial Compaction
4% Asphalt Cement

SECONDARY COMPACTION - 400 REVOLUTIONS AIR-FILLED UPPER ROLLER (VARIABLE ANGLE)		BULK UNIT WEIGHT - PCF		BULK UNIT WEIGHT - PCF	
RAM PRESSURE, PSI	AIR PRESSURE, PSI	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	

TABLE 13
UNIT WEIGHT GRADIENT OF KNEADING-COMPACTED SPECIMENS

Gradation D	ASPHALT CONTENT, %	BULK UNIT WEIGHT - PCF		BULK UNIT WEIGHT - PCF	
		TOP	BOTTOM	TOP	BOTTOM
4		146.0	138.5		7.5
4 $\frac{1}{2}$		147.3	142.9		4.4
5		148.5	142.3		6.2
5 $\frac{1}{2}$		148.2	142.3		5.9
6		151.0	142.9		8.1
6 $\frac{1}{2}$		148.5	144.8		3.7

4% asphalt to a flushed upper surface for the specimen containing 6½% asphalt. No trend relating unit weight gradient and asphalt content was observed.

Particle Orientation

To study the effect of gyratory compaction on particle orientation, selected pieces of long, slender aggregate were placed with their long axes vertical in a plastic clay contained in the gyratory mold. Three samples were then compacted for 400, 1200, and 5400 revolutions using the fixed 1° upper roller in the gyratory testing machine. Particle reorientation can be seen from the photographs shown in Figures 29, 30. The photographs show that the gyratory compaction reoriented the aggregate particles into positions where their long axes lie horizontal. It should be noted that the aggregate forms concentric circles in the reoriented position.

This evidence, although qualitative, indicates that the gyratory compaction tends to produce the horizontal particle orientation similar to that found in pavements under traffic. 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 films. Within the limits imposed by the above 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.

LONG SLENDER AGGREGATE

400 REVOLUTIONS
50 PSI RAM PRESSURE
1° ANGLE OF GYRATION

FIG. 29 STUDY OF PARTICLE ORIENTATION

1200 REVOLUTIONS
40 PSI RAM PRESSURE
1° ANGLE OF GYRATION

5400 REVOLUTIONS
25 PSI RAM PRESSURE
1° ANGLE OF GYRATION

FIG.30 STUDY OF PARTICLE ORIENTATION

SUMMARY OF RESULTS AND CONCLUSIONS

The following section presents results and conclusions which appear to be justified by the experimental data collected. It should be noted that the results and conclusions presented here 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% 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 upon the specimen during testing in the stabilometer. The average increase in bulk unit weight was 1.67 pcf. It was noted that this change in bulk unit weight would be reflected in low estimates of % voids, since such determinations were made after the stabilometer test was performed.
2. Analysis of variance for the five main factors studied in the laboratory showed all factors were significant in affecting specimen compaction as evaluated by change in stability. Factors included were : secondary revolutions, initial pressure, secondary pressure, initial revolutions, and gradation. Data from controlled field studies are necessary to determine whether a realistic simulation of the pavement condition is effected by this laboratory procedure. However, the same statistical methods

could be applied to a field study for an evaluation of field compaction and stability variables.

3. In all cases studied, increases in initial compaction pressure and number of revolutions increased the initial stability. For the initial compaction conditions used, initial stability was less than 30 Hveem stability units for all specimens. For the two mixtures studied, all levels of secondary compaction, whether imposed by a decreased compaction pressure and a greater number of revolutions or by increased compaction pressure, produced additional specimen compaction. Thus it is indicated that, for any given mixture, increased initial compaction will decrease the secondary compaction that can be applied before loss in stability occurs.
4. Axial deformation of specimens under simulated traffic is greater for specimens initially compacted at low pressures than 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. Compaction by the standard Hveem design procedure indicated that the 4% asphalt used for gyratory compaction of the Fuller gradation was optimum. Stability values for kneading- and gyratory-compacted specimens compared favorably for the same values of % 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 for specimens having the same % voids. High stability values were measured for gradation D specimens containing from 4 to 7% asphalt and compacted to 400 revolutions. 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% range of asphalt content studied. It was suspected that excessive degradation in the tops of specimens formed from the more open mixture was responsible for the low stability values measured. It was concluded that 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 with 4% asphalt that were compacted in the gyratory testing machine had variation in unit weight from top to bottom that differed with amount and type of compaction. Unit weights of specimen bottoms tended to be slightly greater than the unit weights 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 types of operation (fixed or air-

filled roller), temperature and mixture composition. Both mixture gradation and asphalt content were factors of composition that influenced stability values. It was found that stability characteristics for specimens compacted using high air pressures in the air-filled upper roller were similar to those obtained from fixed-roller compaction. Air-filled roller compaction using low air pressures did not deform specimens appreciably. For low air pressures gyratory compaction approaches static compaction where kneading action and the movement of aggregate pieces are minimal.

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

SUGGESTIONS FOR FURTHER RESEARCH

Because any laboratory analysis of a design must be tested in the field before its validity can be established, it would be appropriate to determine as closely as possible what conditions exist under traffic in a bituminous resurface layer placed over a portland cement concrete pavement. It is suggested that several test thicknesses be studied. For each test thickness it would be desirable to use a single layer of uniform composition in order that measurements of changes in unit weight with thickness and stability changes during pavement life would not be complicated by a mixture variable. Studies with the gyratory testing machine might then be used to determine what relative compactive efforts would produce the same properties in the laboratory specimen.

Other research might be directed toward investigating more fully the action of the gyratory testing machine with regard to the variable-strain method of operation and toward establishing the value of such operation for judging various mixtures with respect to potential stability and service life. A study of this nature coupled with future pavement correlation studies would help evaluate the applicability of Hveem and gyratory procedures to mixture design.

Another study might involve investigation of the causes for the different stability and voids characteristics observed for open-type mixtures compacted in the kneading compactor and the gyratory testing machine.

Hveem stability is a unitless number. To give the stability number more meaning, a useful project might be to instrument the gyratory testing

machine so that the energy input could be measured. In this way change in stability might be related to the work put into the specimen by the compacting system.

A more fundamental approach to the problem of stability in specimens might be made through utilization of stress and strain repetitions as a means of evaluating changes in strength. How well the bituminous material properties conform to the theory of elasticity might have to be considered in this study. In all cases of application of engineering materials, structural sufficiency must be related to the properties of the materials used. It might be profitable to consider design for strength requirements in terms of test procedures that would include plastic characteristics of mixtures and their response to repetitive loads.

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APPENDIX A

DATA

TABLE 14

HVEEM STABILITY FOR FULLER'S MAXIMUM DENSITY GRADATION
10 REVOLUTION INITIAL COMPACTION

SECONDARY REVOLUTIONS	INITIAL PRESSURE - PSI	SECONDARY PRESSURES - PSI			
		0	50	100	150
30	50	14.1	21.9	28.5	30.2
	100	18.6	26.9	31.6	33.6
	150	24.4	29.2	29.8	34.2
60	50	15.1	24.6	30.7	34.2
	100	21.9	27.8	33.6	37.3
	150	23.9	31.7	33.2	38.0
90	50	15.4	27.8	32.2	37.6
	100	19.6	28.5	35.2	41.0
	150	25.3	31.1	33.9	30.4
400	50	14.9	34.0	37.0	38.4
	100	19.6	44.5	43.0	39.3
	150	24.5	36.0	42.2	34.8

TABLE 15

HVEEM STABILITY FOR FULLER'S MAXIMUM DENSITY GRADATION
20 REVOLUTION INITIAL COMPACTION

SECONDARY REVOLUTIONS	INITIAL PRESSURE - PSI	SECONDARY PRESSURE - PSI			
		0	50	100	150
30	50	17.6	24.9	30.3	30.9
	100	21.4	29.8	30.0	39.4
	150	27.0	34.5	36.1	37.0
60	50	19.4	27.6	32.0	38.3
	100	23.5	29.9	34.6	41.6
	150	27.5	35.0	37.5	36.8
90	50	19.2	29.8	34.6	38.4
	100	21.2	31.6	39.5	42.8
	150	28.0	38.7	38.0	39.6
400	50	19.0	32.8	29.0	23.0
	100	21.7	34.5	36.5	33.5
	150	27.5	39.5	36.5	30.4

TABLE 16

HVEEM STABILITY FOR GRADATION D
10 REVOLUTION INITIAL COMPACTION

SECONDARY REVOLUTIONS	INITIAL PRESSURE - PSI	SECONDARY PRESSURES - PSI			
		0	50	100	150
30	50	15.2	22.0	24.7	30.0
	100	19.3	23.5	28.0	34.5
	150	18.3	24.8	29.6	33.9
60	50	16.0	21.8	29.1	34.4
	100	20.0	25.0	33.6	40.9
	150	22.6	28.1	34.4	39.8
90	50	14.1	25.2	31.7	41.0
	100	20.8	27.9	35.1	42.6
	150	21.6	27.9	38.1	45.3
400	50	15.2	29.9	43.0	46.0
	100	20.0	32.6	41.8	55.0
	150	22.0	39.2	43.7	54.5

TABLE 17

HVEEM STABILITY FOR GRADATION D
20 REVOLUTION INITIAL COMPACTION

SECONDARY REVOLUTIONS	INITIAL PRESSURE - PSI	SECONDARY PRESSURES - PSI			
		0	50	100	150
30	50	19.7	22.2	29.4	34.1
	100	22.0	25.8	30.2	33.8
	150	26.8	33.0	35.9	37.8
60	50	20.5	26.5	34.4	40.0
	100	22.7	28.2	34.0	41.4
	150	28.1	34.9	40.4	45.3
90	50	20.5	27.4	35.2	42.8
	100	24.8	30.7	37.6	41.9
	150	29.2	35.5	41.1	47.7
400	50	20.2	33.6	42.3	49.3
	100	22.9	33.2	40.0	49.0
	150	28.1	38.9	40.6	49.8

TABLE 18

HVEEM STABILITY -VARYING ASPHALT CONTENT

Gradation D

100 Psi, 10 Revolution Initial Compaction

4% Asphalt

Secondary Revolutions	Secondary Pressures - psi			
	0	50	100	150
30	19.3	23.5	28.0	34.5
60	20.0	25.0	33.6	40.9
90	20.8	27.9	35.1	42.6
400	20.0	32.6	41.8	55.0

5% Asphalt

Secondary Revolutions	Secondary Pressures - psi			
	0	50	100	150
30	19.7	22.2	26.3	29.7
60	20.0	25.1	30.0	40.1
90	20.0	26.8	37.5	40.6
400	20.7	33.2	43.6	51.0

6% Asphalt

Secondary Revolutions	Secondary Pressures - psi			
	0	50	100	150
30	17.5	24.5	27.8	31.4
60	19.0	27.6	32.6	39.8
90	20.2	29.6	36.6	42.8
400	19.7	34.6	40.0	45.0

7% Asphalt

Secondary Revolutions	Secondary Pressures - psi			
	0	50	100	150
30	20.0	23.7	28.9	29.8
60	19.7	26.5	32.1	35.6
90	19.7	27.7	33.5	39.4
400	20.0	35.2	37.4	42.0

TABLE 19

DATA FOR KNEADING-COMPACTED SPECIMENS

Fuller's Maximum Density Gradation

ASPHALT CONTENT, %	HVEEM STABILITY	% Voids
3½	39.8	4.8
4	33.4	3.3
4½	27.4	1.2
5	0	0.3
5½	0	0
6	0	0

APPENDIX B
STATISTICAL TESTS

APPENDIX B

Statistical Tests

In this section descriptions of statistical tests used in the study are presented. References in this section refer to the STATISTICAL REFERENCES presented at the end of the REFERENCES section.

Analysis of Variance

An analysis of variance was used to determine whether the variables studied were effective in producing significantly different stabilities in specimens. Data were classified by initial and secondary compaction pressures and secondary revolutions. A single replication was made for each combination of these factors. Assuming a fixed-effects model would be valid, an analysis of variance for a three-way classification with a single case in each class was chosen. The test is described by Duncan (2S) and the following is extracted from this reference.

If $\bar{X}$ is a mean where r , c , g denote the number of rows, columns, groups, and i , j , k denote the individual row, column, or group respectively the following sums of squares are defined:

$$S_1^2 = \frac{cg \sum_i (\bar{X}_i - \bar{\bar{X}})^2}{r - 1}$$

$$S_2^2 = \frac{rg \sum_j (\bar{X}_j - \bar{\bar{X}})^2}{c - 1}$$

$$s_3^2 = \frac{rc \sum_k (\bar{X}_k - \bar{\bar{X}})^2}{g-1}$$

$$s_4^2 = \frac{g \sum_i \sum_j (\bar{X}_{ij} - \bar{X}_i - \bar{X}_j + \bar{\bar{X}})^2}{(r-1)(c-1)}$$

$$s_5^2 = \frac{c \sum_i \sum_k (\bar{X}_{ik} - \bar{X}_i - \bar{X}_k + \bar{\bar{X}})^2}{(r-1)(g-1)}$$

$$s_6^2 = \frac{r \sum_j \sum_k (\bar{X}_{jk} - \bar{X}_j - \bar{X}_k + \bar{\bar{X}})^2}{(c-1)(g-1)}$$

$$s_e^2 = \frac{\sum_i \sum_j \sum_k (x_{ijk} - \bar{X}_{ij} - \bar{X}_{ik} - \bar{X}_{jk} + \bar{X}_i + \bar{X}_j + \bar{X}_k - \bar{\bar{X}})^2}{(r-1)(c-1)(g-1)}$$

The null hypothesis tested is that the variables forming the r , c , g classifications do not significantly effect the value of the x_{ijk} . The hypothesis was tested by computing the s_1^2/s_e^2 and comparing it with the α point of the frequency distribution for $n_1 = \text{d.f. } s_1^2$ and $n_2 = (r-1)(c-1)(g-1)$ degrees of freedom.

Tabulated values of the results of the analysis of variance are included in the section of RESULTS.

A description of the 5-way analysis of variance is described by Ostle in statistical reference 3S.

Newman-Keuls Sequential Range Test

Where some interaction of the r , c , g of the analysis of variance was significant the Newman-Keuls sequential range test was used to make multiple comparison between means. This test was selected because it

was considered (1S) conservative in protecting against Type I error and has a high probability of rejecting the hypothesis when it should be rejected.

Assume the existence of m variables with n levels of each variable. For a significant interaction of any two m 's test the means of each m_i for each level of n_j , where i and j are levels of m and n respectively. The following is a description of the Newman-Keuls test for making multiple comparison between means.

	m_1	m_2	m_3	m_4	...	...	m_i
n_1	$\bar{x}_{11}$	$\bar{x}_{12}$	$\bar{x}_{13}$	...	...	...	$\bar{x}_{1i}$
n_2	$\bar{x}_{21}$						$\bar{x}_{2i}$
.	.						.
.	.						.
.	.						.
n_j	...					...	$\bar{x}_{ji}$

Rank the means from highest to lowest so $\bar{x}_1 = \text{highest}$; $\bar{x}_z = \text{lowest}$.

Form the table:

Rank	$k = z$	$z - 1$	$z - 2$
1	$\bar{x}_1 - \bar{x}_z$	$\bar{x}_1 - \bar{x}_{z-1}$	$\bar{x}_1 - \bar{x}_{z-2}$
2		$\bar{x}_2 - \bar{x}_z$	$\bar{x}_1 - \bar{x}_{z-1}$
3			
4			
.			
.			
.			
$z - 1$			$\bar{x}_{z-1} - \bar{x}_z$

Compare $|\bar{x}_i - \bar{x}_j|$ in order of decreasing k and decreasing rank, rejecting if $|\bar{x}_i - \bar{x}_j| > R_k$ in the columns shown above where $R_k = q_k S_y$.

Where each mean is the average of y values and a fixed model is used then $S_y = \sqrt{\frac{S_e^2}{n_i}}$ and S_e^2 is the error mean square from the analysis of variance. Once one non-significant difference is found in any column the testing may be stopped because the remaining differences are not significant. The differences of means of m are tested for all levels of n and vice versa.

A complete Newman-Keuls sequential range test of one interaction from the analysis of variance is presented in APPENDIX C.

APPENDIX C
STATISTICAL COMPUTATIONS

STATISTICAL COMPUTATIONS

A. Comparison of Speciman Bulk Unit Weight Before and After Stabilometer Test by Method of Differences

Fuller's Maximum Density Gradation

100 psi, 10 revolution, 1° angle compaction

4% asphalt

Data

<u>BULK UNIT WEIGHT - PCF</u>		<u>DIFFERENCE - PCF</u>
(1)	(2)	
BEFORE STABILOMETER TEST	AFTER STABILOMETER TEST	(2) - (1)
142.0	144.1	2.1
141.6	143.5	1.9
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

$$\Sigma d = 16.7$$

$$\bar{d} = \frac{16.7}{10} = 1.67$$

$$\Sigma d^2 = 28.97$$

$$(\Sigma d)^2 = 278.89$$

Assumptions: Matched pair samples, normal populations, equal variability within populations.

H_0 : Stabilometer test does not cause significant change in bulk unit weight.

Level of Significance: Choose $\alpha = 0.05$.

$$t_{n-1} = \frac{\bar{d} - 0}{\sqrt{\frac{n \Sigma d^2 - (\Sigma d)^2}{n^2 (n-1)}}$$

$$t_9 = \frac{1.67}{\sqrt{\frac{(10)(28.97) - (278.89)}{100(9)}}} = 15.24$$

$$t_9 = 15.24 > t_{9, .05} = 2.26$$

Conclusion: Reject H_0 and conclude that stabilometer significantly increases bulk unit weight.

B. Effect of Gyrotory Compaction on Unit Weight Gradient by Method of Differences

Gradation D

10 revolution, 100 psi initial compaction, 1° angle

4% asphalt

Data

SECONDARY COMPACTION			BULK UNIT WT.		BULK UNIT WT.		BULK UNIT WT.
1° ANGLE, PSI	REVOLUTIONS		PCF		PCF		PCF
			TOP	BOTTOM	TOP	BOTTOM	TOP-BOTTOM
50	60		137.3	136.0	2.3	1.0	1.3
50	90		138.5	137.9	3.5	2.9	0.6
100	30		137.9	137.3	2.9	2.3	0.6
100	60		138.5	138.5	3.5	3.5	0.0
100	90		140.4	141.0	5.4	6.0	-0.6
150	30		136.0	138.5	1.0	3.5	-2.5
150	60		141.0	140.4	6.0	5.4	0.6
	none		134.2	132.3	-0.8	-2.7	1.9
	none		134.2	135.4	-0.8	0.4	-1.2

$$\sum d = 0.7$$

Assumption: Matched pair samples, normal populations, equal variability within populations.

Hypothesis: Bulk unit weights of specimen tops and bottoms are not different.

Level of Significance: Choose $\alpha = 0.05$.

$$\bar{d} = .078$$

$$(\sum d)^2 = .49$$

$$\sum d^2 = 14.43$$

$$t_{n-1} = \frac{\frac{\bar{d} - 0}{\sqrt{\frac{n \sum d^2 - (\sum d)^2}{n^2 (n-1)}}}}{\sqrt{F_{1, 8}}} = \sqrt{F_{1, 8}}$$

$$t_{n-1} = \frac{.078}{\sqrt{\frac{(9)(14.43) - .49}{81(8)}}} = 0.181$$

$$t_8 = 0.181 < t_{8, .05} = 2.31$$

Conclusion: Accept H_0 , the unit weight of specimen tops and bottoms is the same.

C. Effect of Gyratory Compaction on Unit Weight Gradient by Method of Differences

Gradation D

10 revolution, 1° angle initial compaction

4% asphalt

Data

INITIAL PRESSURE, PSI	SECONDARY PRESSURE FOR 390 SECONDARY REVOLUTIONS		BULK UNIT WEIGHT CODED AROUND 135, PCF		BULK UNIT W PCF
	1°	ANGLE, PSI	TOP	BOTTOM	TOP-BOTTOM
50	50		6.4	8.1	-1.7
50	100		10.3	12.1	-1.8
50	150		12.0	14.9	-2.9
100	50		9.6	13.0	-3.4
100	100		11.6	13.8	-2.2
100	150		13.2	14.8	-1.6
150	50		10.0	11.0	-1.0
150	100		11.1	12.3	-1.2
150	150		14.6	13.8	0.8

Assumptions: Matched-pair samples, normal populations, equal variability within populations.

H_0 : There is no difference in bulk unit weights of specimen tops and bottoms.

Level of Significance: Choose $\alpha = 0.05$.

$$\bar{d} = 1.67 \quad (\sum d)^2 = 225.00 \quad \sum d^2 = 35.58$$

$$t_{n-1} = \frac{\bar{d} - 0}{\sqrt{\frac{n \sum d^2 - (\sum d)^2}{n^2 (n-1)}}$$

$$t_{n-1} = \frac{1.67}{\sqrt{\frac{(9)(35.58) - 225.00}{81(8)}}} = 4.39$$

$$t_8 = 4.39 > t_{8, .05} = 2.31$$

Conclusion: Reject H_0 and conclude that bulk unit weights of specimen tops and bottoms are different.

D. Effect of Gyrotory Compaction on Bulk Unit Weight Gradient by Method of Differences

Air-Filled Upper Roller

Gradation D

10 revolution, 50 psi initial compaction

1° angle, 4% asphalt

Data

SECONDARY COMPACTION (VARIABLE ANGLE) 400 REVOLUTIONS		BULK UNIT WEIGHT CODED AROUND 135, PCF		BULK UNIT WT. PCF
RAM PRESSURE, PSI	AIR PRESSURE, PSI	TOP	BOTTOM	TOP-BOTTOM
50	25	3.5	4.8	1.3
100	25	3.5	3.5	0.0
150	25	2.3	3.5	1.2
50	50	5.4	6.6	1.2
100	50	8.5	9.1	0.6
150	12	0.4	2.9	2.5
100	12	1.0	1.7	0.7

$$\Sigma d = 7.5$$

Assumptions: Matched-pair samples, normal populations, equal variability within populations.

H_0 : There is no difference in bulk unit weights of specimens tops and bottoms.

Level of Significance: Choose $\alpha = 0.05$.

$$\bar{d} = 1.07 \quad \Sigma d^2 = 11.67 \quad (\Sigma d)^2 = 56.25$$

$$t_{n-1} = \frac{\bar{d} - 0}{\sqrt{\frac{n \Sigma d^2 - (\Sigma d)^2}{n^2(n-1)}}$$

$$t_{n-1} = \frac{1.07}{\sqrt{\frac{(7)(11.67) - 56.25}{(49)(7)}}} = 3.93$$

$$t_6 = 3.93 > 2.45 = t_6, .05$$

Conclusion: Reject H_0 and conclude that bulk unit weights of specimen tops and bottoms are different.

E. Effect of Kneading Compaction on Bulk Unit Weight Gradient by method of Differences.

Gradation D

Hveem Design Procedure Compaction

Data

BULK UNIT WEIGHT - PCF		BULK UNIT WEIGHT CODED AROUND 135, PCF		BULK UNIT WEIGHT PCF
TOP	BOTTOM	TOP	BOTTOM	TOP-BOTTOM
146.0	138.5	11.0	3.5	8.0
147.3	142.9	12.3	7.9	4.4
148.5	142.3	13.5	7.3	6.2
148.2	142.3	13.2	7.3	5.9
151.0	142.9	16.0	7.9	8.1
148.5	144.8	13.5	9.8	3.7

$$\sum d = 36.3$$

Assumptions: Matched-pair samples, normal populations, equal variability with populations.

H_0 : There is no difference in bulk unit weights of specimen tops and bottoms.

Level of Significance: Choose $\alpha = 0.05$.

$$\bar{d} = 6.05 \quad \sum d^2 = 235.91 \quad (\sum d)^2 = 1317.79$$

$$t_{n-1} = \frac{\bar{d} - 0}{\sqrt{\frac{n \sum d^2 - (\sum d)^2}{n^2 (n-1)}}}$$

$$t_{n-1} = \frac{6.05}{\sqrt{\frac{(6)(235.91) - 1317.79}{36(5)}}} = 8.29$$

$$t_5 = 8.29 > t_{5, .05} = 2.57$$

Conclusion: Reject H_0 and conclude that bulk unit weights of specimen tops and bottoms are different.

NEWMAN-KEULS ANALYSIS

Secondary Pressure - Secondary Revolution Interaction

Gradation D

10 Revolution Initial Compaction

4% Asphalt

1° Angle of Gyration

 H_0 : There is no significant difference in stabilitiesLevel of Significance: Choose $\alpha = 0.05$.

Secondary Revolutions		Secondary Pressure - Psi				Line
		0	50	100	150	
30	totals	52.8	70.3	82.3	98.4	A
	means	17.6	23.4	27.4	32.8	
60	totals	58.6	74.9	97.1	115.1	B
	means	19.5	25.0	32.4	38.4	
90	totals	56.5	81.0	104.9	128.9	C
	means	18.8	27.0	35.0	43.0	

$$R_k = q_k S_y = q_k \sqrt{\frac{1.27}{3}} = 0.648 q_k$$

$$q_k = 4.20 \quad 3.77 \quad 3.08$$

$$R_k = \frac{2.72}{4} \quad \frac{2.44}{3} \quad \frac{2.00}{2}$$

$$K \quad 4 \quad 3 \quad 2$$

Ranking the means of line A:

$$\bar{x}_1 = 32.8, \bar{x}_2 = 27.4, \bar{x}_3 = 23.4, \bar{x}_4 = 17.6$$

Rank	K	4	3	2
1		15.2*	9.4*	5.4*
2			9.8*	4.0*
3				5.8*

From line B:

$$\bar{X}_1 = 38.4, \bar{X}_2 = 32.4, \bar{X}_3 = 25.0, \bar{X}_4 = 19.5$$

Rank	K	4	3	2
1		18.9*	13.4*	6.0*
2			12.9*	7.4*
3				5.5*

From Line C:

$$\bar{X}_1 = 43.0, \bar{X}_2 = 35.0, \bar{X}_3 = 27.0, \bar{X}_4 = 18.8$$

Rank	K	4	3	2
1		24.2*	16.0*	8.0*
2			16.2*	8.0*
3				8.2*

* - reject H_0

** - accept H_0

Secondary Pressure - Psi	Secondary Revolutions				Line
		30	60	90	
0	totals	52.8	58.6	50.5	A
	means	17.6	19.5	18.8	
50	totals	70.3	74.9	81.0	B
	means	23.4	25.0	27.0	
100	totals	82.3	97.1	104.9	C
	means	27.4	32.4	35.0	
150	totals	98.4	115.1	128.9	D
	means	32.8	38.4	43.0	

$$R_k = q_k S_y = q_k \sqrt{\frac{1.27}{3}} = 0.648 q_k$$

K	=	3	2
q_k	=	3.40	3.26
R_k	=	<u>2.20</u>	<u>2.11</u>

Ranking the means of line A:

$$\bar{x}_1 = 19.5, \bar{x}_2 = 18.8, \bar{x}_3 = 17.6$$

Rank	K	3	2
1		1.9**	0.7**
2			1.2**

$$\begin{aligned} K &= 3 & 2 \\ R_k &= \underline{2.20} & \underline{2.11} \end{aligned}$$

From line B:

$$\bar{x}_1 = 27.0, \bar{x}_2 = 25.0, \bar{x}_3 = 23.4$$

Rank	K	3	2
1		3.6*	2.0**
2			1.6**

From line C:

$$\bar{x}_1 = 35.0, \bar{x}_2 = 32.4, \bar{x}_3 = 27.4$$

Rank	K	3	2
1		7.6*	2.6*
2			5.0*

From line D:

$$\bar{x}_1 = 43.0, \bar{x}_2 = 38.4, \bar{x}_3 = 32.8$$

Rank	K	3	2
1		10.2*	4.6*
2			5.6*

* - reject H_0

** - accept H_0