EVALUATION OF THE TTI GYRATORY COMPACTOR

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PREFACE

This is the third report issued under Research Study 2-8-65-99, Stress Distribution in Granular Masses, being conducted at the Texas Transportation Institute as part of the cooperative research program with the Texas Highway Department and U. S. Bureau of Public Roads.

The first two reports are:

"The Use of Particulate Mechanics in the Simulation of Stress-Strain Characteristics of Granular Materials," by James C. Armstrong and Wayne A. Dunlap, Research Report 99-1, Texas Transportation Institute, August, 1966.

"A Gyratory Compactor for Molding Large Diameter Triaxial Specimens of Granular Materials," by Lionel J. Milberger and Wayne A. Dunlap, Research Report 99-2, Texas Transportation Institute, October, 1966.

The authors wish to thank all members of the Institute who assisted in this research. They would like to express special appreciation to Mr. Frank H. Scrivner for his advice and assistance. His help throughout the study was particularly valuable. Special gratitude is also expressed to Mr. George Darroch for his advice concerning experiment design and statistics throughout the study, Mr. Chester H. Michalak for his suggestions during the development of the compaction procedure, Messrs, Charles E. Schlieker and Donald J. Hollinger for their help during the testing phase, and Mr. M. B. Phillips for his help in preparing this report.

The authors also wish to thank Mr. James L. Brown, the Texas Highway Department Study Contact Representative, for his assistance and support in this research.

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

ABSTRACT

This report describes the evaluation of a gyratory compactor developed by the Texas Transportation Institute for the sole purpose of producing specimens of high uniformity for repetitive triaxial testing. The material selected for use in the evaluation was a crushed limestone. In prior investigations replicate specimens made from this limestone exhibited somewhat erratic behavior. In fact, of the several materials tested this material was by far the most troublesome. Nevertheless, it is an excellent flexible base material and widely used in this state.

The evaluation of the compactor resulted in an operating procedure that will produce nearly identical test specimens of this material over a wide range of moisture contents and densities. It was found that compacted specimens had replication errors in density of less than 0.4 pcf, in moisture content of less than 0.1 per cent, and in unconfined compressive strength of less than 8 psi. The authors believe that the observed replication errors are smaller than is now possible with any other known method of preparing similar specimens of granular materials for testing. Also, it is believed that the replication errors are of the same order of magnitude as now accepted in standard concrete, brick, and wood testing.

Equations were developed that relate the compacted density and moisture content of the limestone specimens to the molding moisture content and compactor variables. These equations show that test specimens can be prepared over a wide range of preselected moisture contents and densities. Expected errors in the preselected moisture contents and densities of test specimens are less than 0.2 per cent for moisture content and less than 1.0 pcf for density.

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1. INTRODUCTION

The preparation of specimens of granular material for laboratory testing has traditionally been a difficult art. Dunlap reported erratic behavior of replicate specimens of granular materials subjected to rapid, repetitive loading which he attributed, in large part, to the method of preparing test specimens (1).* He used the Texas Highway Department impact method of compaction, and he felt that the hand finishing required to level the compacted specimen's top surface was an inherent weakness in the method.

The first year's effort in this research study was devoted to finding a better method of preparing test specimens. A study of all methods of specimen preparation resulted in the fabrication of a gyratory compactor for molding large diameter test specimens. Known as the Texas Transportation Institute Gyratory Compactor, it is pictured in Figure 1. Details of the design and operation of the compactor were reported in Research Report 99-2 (2).

The purpose of this report is to present an evaluation of the ability of the compactor to accomplish its basic design objectives. More specifically, the evaluation is directed toward answering the following two questions: a) can the compactor fabricate specimens which are uniform in density,

*Numbers in parentheses refer to reference numbers listed in Section 8.

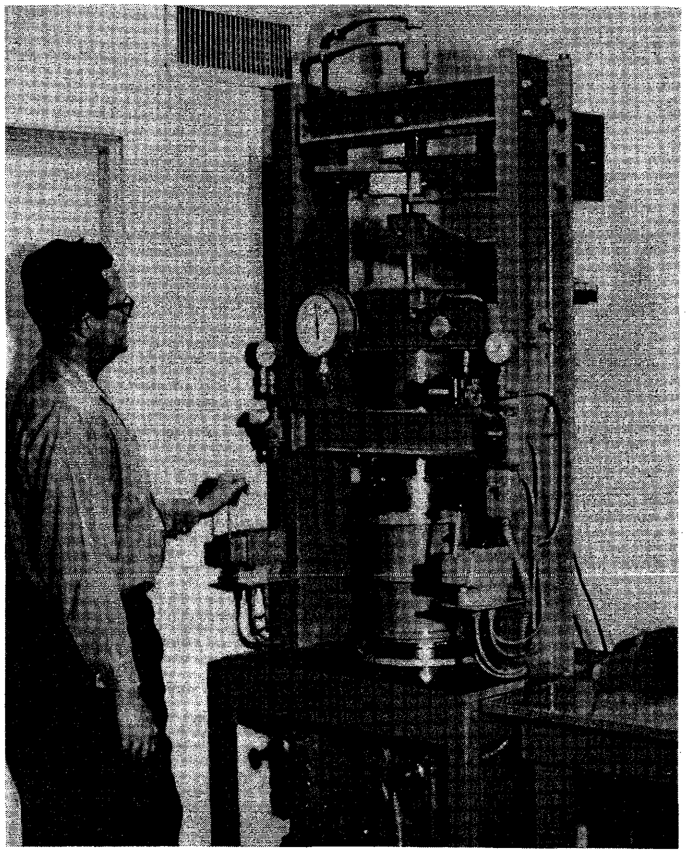

FIGURE 1 - COMPACTOR IN OPERATION

moisture content, and gradation and b) can it fabricate nearly identical replicate test specimens over wide ranges of moisture content and density? It was felt that affirmative answers to these two questions would result in more suitable specimens for laboratory testing than had ever before been possible.

The compactor evaluation was divided into two distinct phases. The first, described in Sections 3 and 4, was the development of a compaction procedure and the second, described in Sections 5 and 6, was an evaluation of the compactor's capability utilizing the procedure to fabricate nearly identical replicate test specimens over a wide range of compactive effort. As a result of the evaluation, a satisfactory operating procedure was developed and is given in Appendix A. Also, it was found that replicate specimens compacted in accordance with the procedure were nearly identical and that they could be prepared over a range of moisture contents and densities. Thus, the evaluation led to affirmative answers to the questions asked in the preceding paragraph. The authors believe that the compactor produces more uniform specimens over a wider range of moisture content and density than was previously possible.

2. MATERIAL AND SPECIMEN PREPARATION

The material selected for the compactor evaluation was a crushed limestone obtained from the Servtex Limestone Company, New Braunfels, Texas. This material was selected primarily because of past difficulties experienced in obtaining similar behavior of replicate specimens made from the material. It has been by far the most troublesome of several materials tried. Nevertheless, field experience has shown it to be an excellent flexible base material, and it is widely used in this state. Table 1 gives a summary of its engineering properties.

In processing, the material was air dried for at least four days, oven dried at 140°F. for at least 48 hours, and then separated on a Gilson sieve-shaker on sieves of the following sizes: 1 1/2", 1", 3/4", 3/8", #4, #10, and pan. These fractions, which are illustrated in Figure 2, were stored in separate containers until needed for the recombination of a sample. Throughout the research the fractions were combined in order to make approximately 2" of compacted specimen having the gradation given in Table 1. The material fractions were combined with water to obtain the desired moisture content and mixed in a counter-current batchmixer for two minutes. After mixing, the material for each 2" layer was stored separately in a humid room in an air-tight container for a minimum of

24 hours to allow for uniform distribution of moisture. The material was then ready for compaction. It should be noted that the material was not compacted in layers, only mixed and placed in the mold in layers in order to achieve uniformity in moisture and particle distribution.

TABLE 1

ENGINEERING PROPERTIES OF SERVTEX CRUSHED LIMESTONE

LL	PI	SL	LS	SR	WET BALL MILL	L.A. ABRASION	SPECIFIC GRAVITY	TEXAS CLASSIFICATION
15	4	12	1.0	1.97	31	32	2.66	TYPE A GRADE I

GRADATION													
PERCENT RETAINED ON													
OPENING – in.				SIEVE NUMBER						OPENING – mm.			
1 1/2	1	3/4	3/8	4	10	20	40	80	200	.05	.005	.001	-.001
0	16	26	42	50	57	73	80	85	88	90	93	97	100

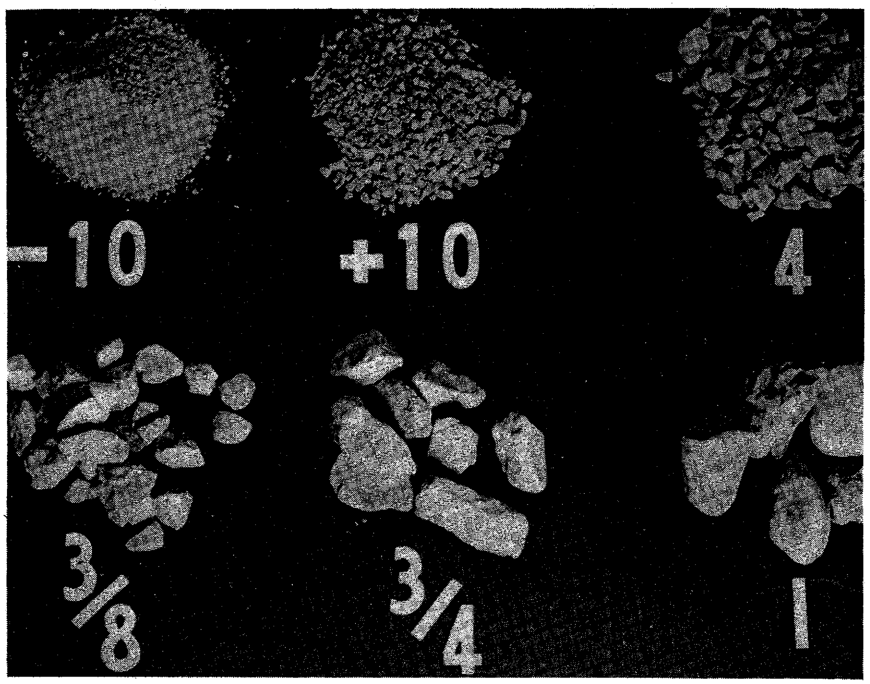

FIGURE 2 - FRACTIONS USED TO RECOMBINE SPECIMEN

3. STABILIZED SPECIMENS USED IN DEVELOPMENT OF COMPACTION PROCEDURE

Many variations in compaction procedure were tried in order to develop a suitable method of molding specimens and each procedure was evaluated primarily by examining the density variations within the compacted specimens. During this phase of the investigation, the specimens were cement-stabilized in a manner similar to the procedure used by Parsons (3). After compaction and curing, they were sawed into parts, coated with wax, and the density determined on the several parts.

These specimens were prepared as described in the following paragraphs. A specific quantity of minus 200 material (6 per cent of total dry weight) was sieved from each two-inch layer of the sample. The layer was mixed with 94 per cent of the required water for the desired moisture content, and then allowed to cure in air-tight containers for 24 hours in a humid room. Just before compaction, cement (equal in weight to the weight of minus 200 material removed) was mixed with the soil and the remaining 6 per cent of the required water was added while mixing. After compaction, the specimens were placed in a humid room with membranes over them and allowed to cure for seven days in capillarity. The specimens were then oven-dried at 105°C. to a constant weight (a minimum of 48 hours), their weight was recorded, and they were marked for sawing into several horizontal sections, as shown in Figure 3. The specimens were sawed by means of a Clipper masonry saw with a diamond blade. The individual parts were again dried at 105°C. to a constant weight (a minimum of 48 hours) and the dry weights recorded. The parts were then coated with Humble Microvan wax as described below.

The wax was heated above the melting temperature and allowed to cool until a thin film formed on top, immediately after which the parts were coated. Three dippings were required to thoroughly coat each part. Specific gravity of the wax was determined each time that the container was heated or new wax was added. After coating, the parts were allowed to cool to room temperature. Their weight was then taken both in air and in water. From this information the density of each part was calculated.

Several specimens were also sawed into vertical sections as shown in Figure 4 and the density was determined of the individual parts. It was found that the horizontal density gradient determined from these parts was not significant when compared to the vertical gradient found from the samples sawed into horizontal sections.

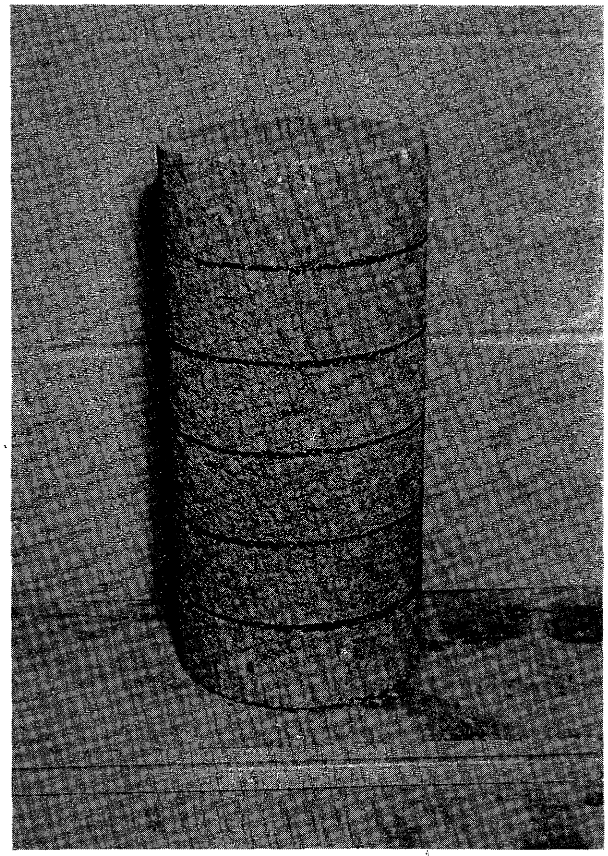

FIGURE 3 - SPECIMEN MARKED FOR SAWING INTO HORIZONTAL SECTIONS

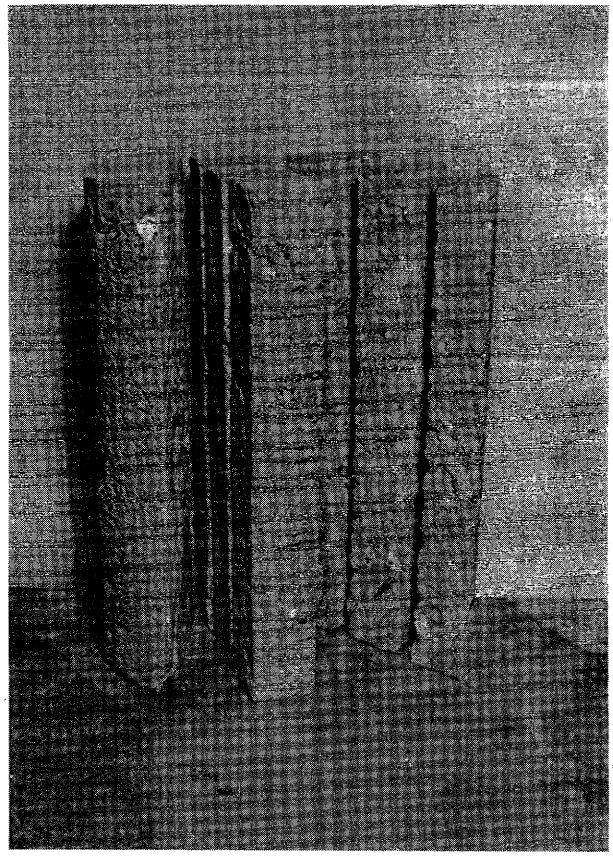

FIGURE 4 - SPECIMEN SAWED IN VERTICAL SECTIONS

4. DEVELOPMENT OF COMPACTION PROCEDURE

The first phase of the compactor evaluation was the development of a compaction procedure for the Texas Transportation Institute Gyratory Compactor that would produce uniform specimens suitable for testing. The compactor was designed solely for this purpose. A wide latitude in compactive effort can be obtained with the compactor through the manipulation of the following four compactor variables:*

a) The average vertical pressure on a specimen can be varied up to 500 psi.

b) The maximum gyratory angle can be varied up to 4 degrees, and it can be returned to zero to level the specimen at any desired rate.

c) The number of gyrations can be preset at any number up to the limit of the counter switch (5 digits).

d) The speed of gyration can be adjusted up to a maximum of 25 gyrations per minute.

After a period of trial operation of the compactor, a limited number of specimens 6 inches in diameter and 12 inches in height were compacted. The procedure used is outlined below:

a) The average vertical pressure was held constant at 250 psi.

* Complete details of the compactor variables are given in reference 2.

b) The maximum gyratory angle was set at 3 degrees and the last three gyrations were used to level the specimen.

c) 100 was set on the counter switch. (At count 97 the operator began to decrease the gyratory angle at a rate so that the angle would be zero at count 100.)

d) The speed of gyration was set at 10 gyrations per minute.

Many specimens were similarly compacted at vertical pressures ranging from 200 to 400, maximum gyratory angles ranging from 1 to 4 degrees, number of gyrations ranging from 5 to 20 gyrations per minute.

The last three gyrations were always used to level the specimen. Replicate specimens compacted using this procedure seemed to be almost identical and cross-sections of the specimens showed no particle segregation. However, two major problems were noted. The first was the presence of a significant vertical density gradient in the specimens; the top and bottom were considerably denser than the center. The other problem was the appearance of a "dome" on the ends of the specimen (see Figure 5). The dome and the density gradient appeared to be more pronounced on specimens compacted at the higher levels of compactive effort.

Initially it was thought that the solution to these two problems lay in the development of a proper procedural use of

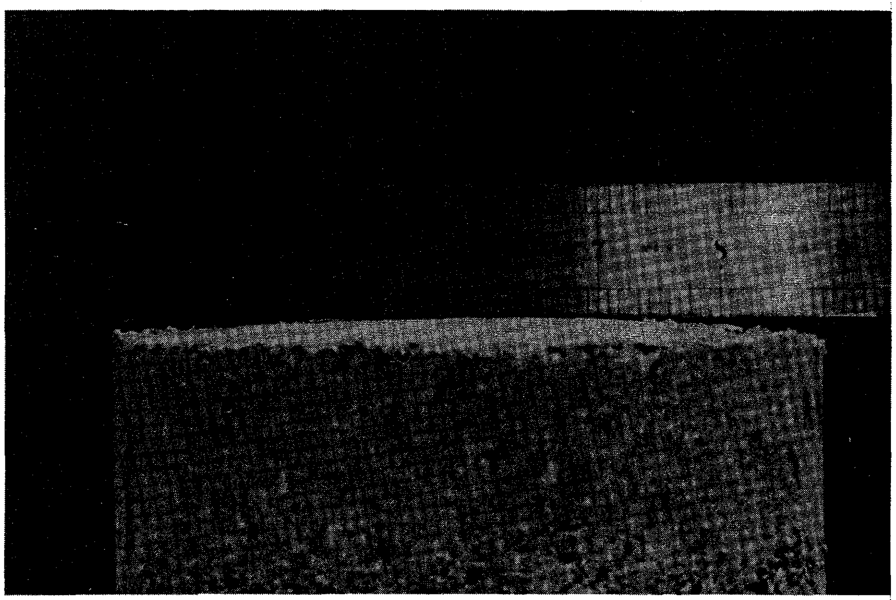

FIGURE 5 - DOME WHICH APPEARED ON INITIAL COMPACTED SPECIMEN

the various compactor variables. In other words, it was felt that good test specimens could be made if the right combination of compactor variables was used.

Many variations in procedure were then tried in an attempt to produce suitable test specimens by eliminating the domes and density gradients. The more significant ones are outlined below:

a) Provision was made on the compactor for applying the vertical load at a very slow rate (as low as .05 inch/minute) after gyration was begun. Trials were made at applying the full load over the first five gyrations. This variation in procedure had no significant effect on the compacted specimens.

b) Although it was not the purpose of the compactor to compact specimens in layers, several methods were tried for compacting in layers. Attempts included two 6" layers, an 8" layer with two 2" layers on top and bottom, and six separate 2" layers. In all instances the results obtained were highly unsatisfactory. The six 2" layers did seem to reduce the density gradient, but the compacted specimens were distinctly layered and were not suitable for test specimens.

c) Each layer of the specimen was compacted statically and then the entire specimen was compacted dynamically. After each layer of the sample was placed in the mold, the vertical load to be used during compaction was applied. The entire sample was then gyrated for various numbers of revolutions. This variation in procedure resulted in slightly higher densities; however, it did not have any significant effect on the two major problems.

d) A variation of the Texas Highway Department method for compacting gyratory asphalt specimens was tried. An average vertical pressure of 50 psi was applied to the sample and the distance between the upper and lower plates held constant by closing a hydraulic valve. The specimen was then gyrated for five revolutions. The vertical pressure was again applied, the hydraulic valve closed, and the specimen gyrated again for five revolutions. This procedure was repeated for several cycles. The sample was then leveled and a seating load equal to an average vertical pressure of 500 psi was applied. The purpose of the seating load was to make a right circular cylinder. The specimens that were made using this procedure might have been more satisfactory if the final seating load could have been considerably higher (the compactor was designed for a maximum average vertical pressure of 500 psi).

e) In addition to using a Teflon impregnated ceramic lined mold, several specimens were compacted using sheet Teflon to line the mold. The Teflon lining seemed to reduce the density gradient somewhat, but the lining wrinkled and shredded during compaction. The surfaces of the specimens were extremely rough and were not suitable for test specimens.

f) Various lubricants were tried on the mold to reduce the friction between the soil particles and the walls of the mold. Ordinary grease, motor oil and graphite, with both heavy and light coats were used. These lubricants also seemed to reduce the density gradient, but specimens impregnated with lubricant were not suitable for testing.

g) Two air vibrators were installed on the mold chuck, and several specimens were gyrated while also being vibrated. The time of vibration and the number of gyrations were varied. No effect from the vibrators could be noted.

h) An experiment was conducted in which the number of revolutions used to level the specimen was varied. From the results obtained from this experiment it was found that the dome at the top and bottom of the specimen could be reduced or eliminated when the specimen was leveled over the entire number of revolutions selected to compact the specimen. After this finding the procedure became standard. That is, the maximum vertical pressure was applied to the specimen and then the gyratory angle was applied. At the same time that gyration was started, the flow restrictor valve that controlled the gyratory angle was opened, and the angle was slowly returned to zero. The rate of change of gyratory angle was held constant, and it was set so that on the desired last count the angle was equal to zero. This procedure required the installation of a more accurate flow restrictor valve than had been used previously.

i) In an experiment to determine the effect of the compactor variables, it was found that the first three, the vertical pressure, the gyratory angle, and the number of gyrations greatly influenced the density of the specimens, whereas the last variable, the speed of gyration, had little or no effect. Thus, to simplify the evaluation, an arbitrary operating speed of 10 gyrations per minute was chosen and this speed was used throughout the remaining tests.

At this point in the evaluation there seemed to remain but one major problem, the large vertical density gradient. In order to determine which of the three remaining variables had the most effect on the density gradient, a special experiment was conducted. The results of this experiment are given in Table B-1, Appendix B. The only significant finding of the experiment was that the density gradient increased as the compactive effort increased, that is, specimens having the highest density also had the highest density gradient. This gradient was about 11 pcf in specimens having an average density of about 139 pcf, and it was about 5 pcf in specimens having an average density of 131 pcf. The standard deviation of the density of the specimen parts from their mean value was 4.07 pcf.

To the authors' knowledge, the problem of density gradients in compacted specimens has been given little treatment in technical literature. Because other gyratory compactors known to the authors* were designed primarily to compact asphaltic specimens having a height to diameter ratio of one or less, it appeared that shorter specimens should be attempted. Several 6" high specimens were prepared and compacted, and the results of these tests were very encouraging. The 6" specimens had density gradients of about 2 pcf or less.

*The gyratory compactors designed by the Waterways Experiment Station (4)(5), Ohio Department of Highways (6), and the Texas Highway Deparment.

With the success obtained in compacting 6" high specimens, additional specimens having a height of 8" were prepared and compacted. The results of these tests are given in Table B-2, Appendix B. Density gradients in these specimens also appeared to be very small. The standard deviation of the density of the specimen parts from their mean value was 1.31 pcf. That is, about two thirds of the time the variation of the specimen parts from their mean value was less than 1.31 pcf.

A few specimens were compacted at heights of 9", 10" and 11". Severe density gradients were present in all of these specimens. It might be noted, however, that for these tests wooden blocks were used for spacers as expedients. It is believed that these blocks may have contributed somewhat to the increase in density gradient. In any event these tests were very limited and are not considered to be conclusive.

Since 8 inches is the height used for triaxial testing by the Texas Highway Department and since satisfactory results were obtained when compacting specimens of 8 inches, it was decided to use this height as standard for test specimens. The shorter height will magnify the compression end effect problem, i.e., the effect of frictional forces acting on the ends of the specimens (7). But the end effects must be considered in stress-strain analysis regardless of the height chosen; therefore, the advantage of having more homogenous test specimens is believed to outweigh the disadvantage of the increased end effect.

Details of the compaction procedure that evolved from the testing described in this section are given in Appendix A. It involves two major changes in the initial operating procedure. The gyration angle is decreased at a constant rate over the entire number of gyrations, and a height of 8" is used instead of 12".

5. EXPERIMENT FOR DETERMINING COMPACTOR CAPABILITIES

Once a definite compaction procedure was settled upon as described in the previous section, the second phase of the compactor evaluation was begun. The purpose of this phase was to determine the capability of the compactor to produce test specimens of various moisture contents and densities utilizing the newly developed procedure. The results of the experiments conducted during this phase are given in Appendix C.

In this phase of the investigation three levels of each of three compactor variables--vertical pressure, gyratory angle, and number of gyrations--were used to encompass approximately the practical range of compactive effort. Because of the finding in the first phase that the fourth compactor variable, rate of gyration, had no significant effect on compactive effort, the rate was held constant at 10 gyrations per minute. The levels of the compactor variables used are as follows:

a) Vertical pressure - 100, 200, and 300 psi.

b) Gyratory angle - 2, 3, and 4 degrees.

c) Number of gyrations - 10, 30, and 50.

During this experiment specimens were prepared as if they were to be used as test specimens. They were not stabilized and their heights were maintained at 8 inches plus or minus

0.10 inch. The height requirement made it necessary to adjust the weights of materials used in each layer based on the expected compacted density.

Specimens were compacted at molding moisture contents ranging from 0 to 7 per cent. The specimens compacted at 0 per cent moisture were very difficult to replicate, and they would not stay in one piece when the mold was removed. Nevertheless, the density of many of these specimens could be obtained without removing them from the mold. The specimens molded at moisture contents of 1 percent and higher had sufficient cohesion to permit removal from the mold, and they could have been used for triaxial testing.

Moisture and fines bled from the ends of the mold when the molding moisture content was 6 per cent and higher. This phenomenon was also observed by both Parsons (3) and Al-Layla (8). The bleeding was so severe in specimens molded at 7 per cent moisture and higher that it was extremely difficult to replicate specimens. Because of the large loss of fines in specimens experiencing severe bleeding, those molded at 7 per cent moisture and higher were not considered to be suitable for testing nor for further study.

6. ANALYSIS OF THE EXPERIMENT

A prime objective of Research Study 2-8-65-99 is "to test the validity of and refine as necessary a deformation hypothesis developed in Study 2-8-62-27, particularly as the hypothesis relates to in-situ gradations, moisture contents, and densities existing during the life of a flexible pavement structure" (9). In order to relate accurately the effect of moisture content and density to the behavior of materials, it is necessary to be able to pre-select the moisture content and density of test specimens. The most practical means of accomplishing this goal was to develop mathematical models relating test specimen moisture content and density to the molding moisture content and the compactor variables. A well fitting mathematical model would also serve the purpose of defining the magnitude of the error that would exist in experiments dependent upon controlling moisture content and density.

The variables considered for inclusion in the model were the molding moisture content, the compactor variables (vertical pressure, gyratory angle, and number of gyrations), the final moisture content and the final compacted density. The molding moisture content and the compactor variables were the independent or controlled variables entering into the model. The final moisture content and the compacted density were both dependent or response variables. The results from tests performed on 171 specimens that were used in the analysis leading to the modeling of these variables are given in Table C-1, Appendix C. Figure 6 illustrates graphically the range of the moisture-density combinations covered by the experiment.

Early in the analysis it was observed that the final moisture content after compaction was primarily a function of the molding moisture content and not a function of the compactor variables. In fact the final moisture content could be estimated from the following equation which has a standard deviation of 0.11% moisture.

$$w = m - 0.0141m^2 \qquad (1)$$

where

w = Final moisture content, per cent of dry weight

m = Molding moisture content, per cent of dry weight

The replication error for moisture content (determined in a standard analysis of variance) was 0.08 per cent. Because it is impossible for any mathematical model to have a standard deviation less than or equal to the replication error, the above equation was considered satisfactory. As indicated by the equation, specimens molded at 6 per cent moisture were found to contain about 5.5 per cent moisture after compaction. The loss in molding moisture indicated by the second term of the equation must have been largely due to losses occurring during mixing, storing, and compaction and not the compactor variables.

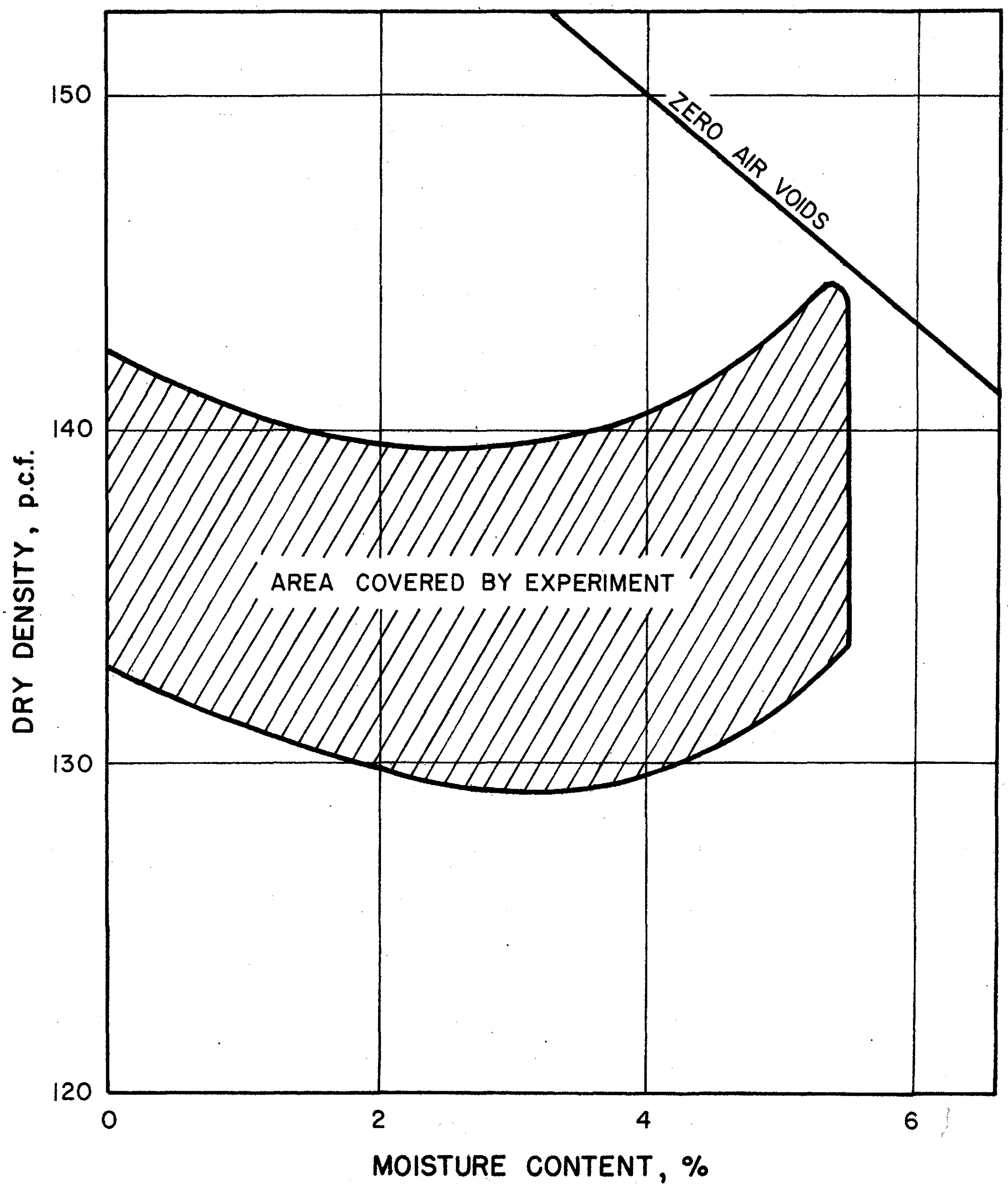

FIGURE 6 - RANGE OF MOISTURE-DENSITY COMBINATIONS COVERED BY THE EXPERIMENT.

Many different mathematical models were tried for predicting the compacted density from the compactor variables and the molding moisture content. It was found that the model could be greatly simplified if the final density based on total weight of the wet specimen was used instead of the conventional density based on the oven dried condition. The conventional density based on the dry weight of the specimen can be easily calculated if the compacted density based on the wet weight and the final moisture content are known.

From the mathematical models tried, the following equation was found to be the most satisfactory.

$$\gamma_w = 138.10 + 0.04784m^3 + 1.912Q + 0.1198mQ \qquad (2)$$

where

γ_w = compacted density based on total weight, pcf.

m = molding moisture content, per cent of dry weight.

Q = compactor variable function that is defined by the following equation:

$$Q = \log_e \left(\frac{Rev}{30}\right)\left(\frac{VP}{200}\right)^{1.681}\left(\frac{GA}{3}\right)^{1.885} \qquad (3)$$

and

Rev = number of gyrations

VP = applied vertical pressure

GA = maximum gyratory angle

The linear numerical coefficients in the above equation for compacted density and the exponents in the compactor variable function were found by using a least square regression technique that is described in Appendix D.

The standard deviation of the compacted density equation was 0.96 pcf which is greater than the replication error of 0.33 pcf determined in an analysis of variance. It should be recognized, however, that the data used to determine the replication error were somewhat biased by discarding (as outlined in Section 5) those specimens that did not meet the height requirement of 8 inches plus or minus 0.1 inch, a procedure that tended to minimize density replication errors. Nevertheless, the standard deviation of internal variations in density within a specimen was 1.31 pcf (see Section 4); thus, the model's prediction error lies between that value and the replication error. The model was, therefore, considered satisfactory. It is the authors' hope that the same model, perhaps with different regression constants, will adequately represent materials other than the crushed limestone used for this evaluation.

In addition to developing a mathematical model relating the experimental variables, and determining replication errors, additional sets of specimens were prepared for performing standard unconfined compression tests. For this experiment three replicate specimens were compacted at three different compactive efforts and at two or three levels of moisture content (see Table C-2, Appendix C). The within sample standard deviation for the unconfined compressive strength was 7.1 psi and the coefficient of variation was 13 per cent. Similarly, the within sample standard deviation of per cent strain was 0.11 per cent, and the coefficient of variation was 11 per cent.

The authors believe that replication errors reported here for the crushed limestone are comparable to replication errors found when testing many other materials and are, therefore, indicative of very small differences in specimens. It is concluded that the Texas Transportation Institute Gyratory Compactor can be used to make very satisfactory test specimens for repetitive triaxial testing.

7. FINDINGS

Listed below are the more significant findings which were reached as a result of the investigation discussed in this report:

1) The procedure given in Appendix A for the Texas Transportation Institute Gyratory Compactor can be used to prepare specimens 8" in height and 6" in diameter that will be suitable for triaxial testing. Generally, specimens having a greater height will not be suitable.

2) By controlling the molding moisture content and varying the compactive effort over a wide range, specimens having a range of densities and moisture contents can be produced. These specimens may be used in studying the effect of moisture content and density on the deformation characteristics of material subjected to repetitive loading with expected errors in the test specimens less than 0.11 per cent for moisture content and 1.0 pcf for density.

3) The highest densities of the research material (Servtex Crushed Limestone) can be obtained at moisture contents approaching complete saturation; however, fines and moisture bleed from these specimens making

it very difficult to secure reproducibility under these conditions.

4) Variation between replicate specimens prepared with the compactor are no greater than variations encountered between replicate specimens for use in standard concrete or wood testing. For example, the replication error in density is 0.6, and in unconfined compressive strength the replication error is 6 psi.

During the investigation, it was found that the compactor needed two modifications not described in Research Report 99-2. That report indicated that a set of plans and a parts list were available to interested parties. These plans have been changed to include the modifications listed below.

1) A more accurate flow restrictor valve controlling the gyratory angle.

2) A 4" high spacer block for use in compacting 8" high specimens in accordance with the recommended procedure given in Appendix A.

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APPENDIX A - OPERATING PROCEDURE

The operating procedure for the Texas Transportation Institute Gyratory Compactor reported herein is divided into two parts. The first part deals with adjustments and settings of the various compactor variables which, once set, remain constant for a given series of tests. The second part of the procedure describes the steps to be allowed for compacting a specimen with the gyratory compactor. Refer to Figure A-1.

I. Compactor Settings and Adjustments

A. Turn on pump unit using Switch Z. Allow pump to run for a minimum of 15 minutes before using to allow hydraulic oil to reach a uniform temperature.

B. Gyratory angle - The maximum angle of gyration is set by moving stop screw "A" on upper rotating plate. To change the gyratory angle, loosen the large retaining nut and turn the stop screw the required number of revolutions to obtain the desired angle setting. (12 1/4 revolutions of the stop crew equals approximately 1°).

C. Number of revolutions - Pre-set counter "B" to cut off the compactor at the desired number of gyrations.

D. Vertical pressure - Vertical pressure on the sample is set on gage C or D. With pump unit running and

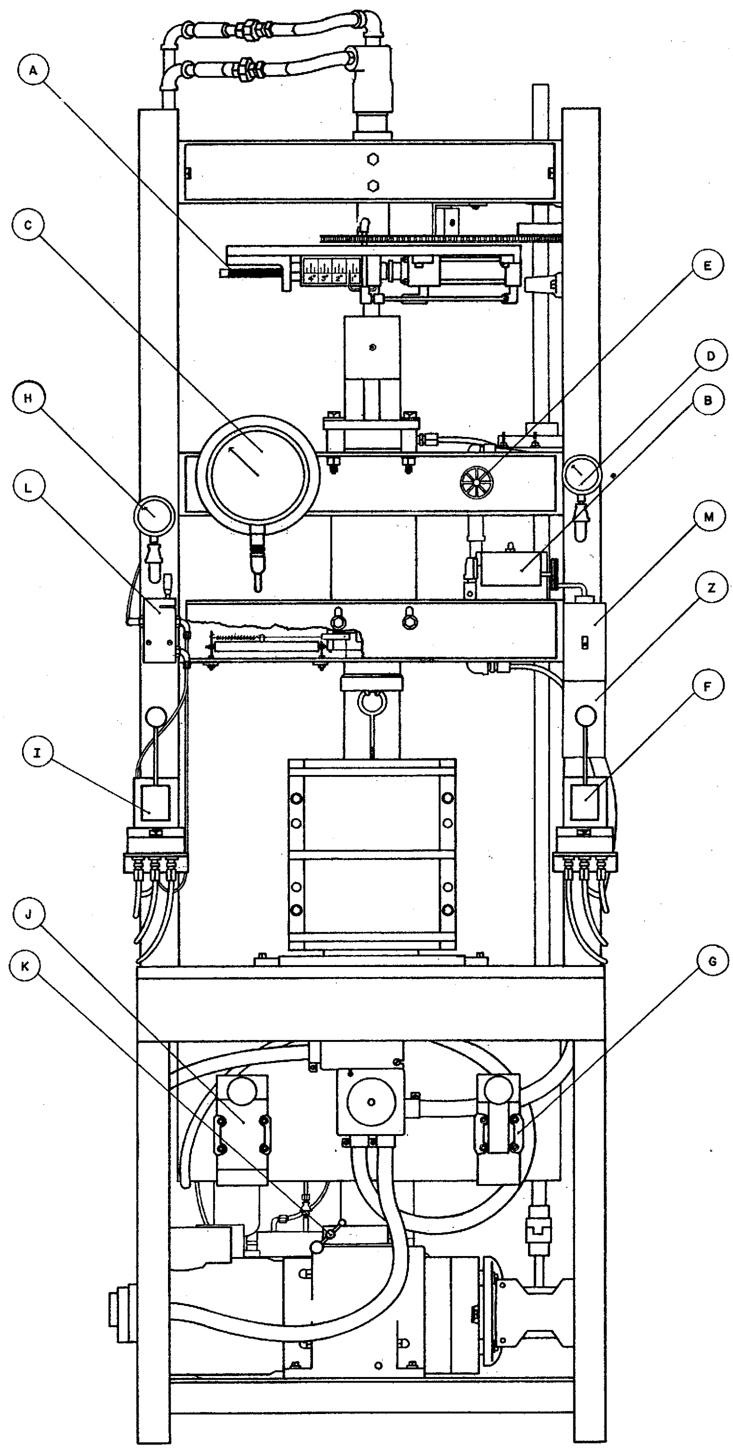

FIGURE A-1 - GYRATORY COMPACTOR

valve "E" closed, move handle of valve "F" to "Load On". Adjust pressure regulator "G" for the desired vertical load. Pressure gauge reading should be first calibrated with vertical load.

E. The pressure needed to decrease the gyratory angle and level the sample is read on gauge "H". Move handle on valve "I" to "Angle On" and adjust regulator "J" until gauge "H" indicates 500 psi.

F. Speed of gyration - Set speed of gyration to 10 gyrations per minute with hand crank "K". The speed should be calibrated with dial settings.

G. Set the micrometer flow restrictor valve "L" so that the angle is brought back to zero in the desired number of revolutions. The valve should be calibrated for various angles and numbers of revolutions.

With these preliminary settings of the compactor variables made, the compactor is ready for operation. It should be noted that once made, these settings need not be changed for any series of similar tests. However, if desired, any one or all the variables can be changed by repeating the appropriate steps outlined above.

II. Compaction of Specimens

A. Place slip rings on the base plate, tighten the circumferential bands around the mold and place the mold on the base plate.

B. Place one layer of the sample in the mold. Insure that a thin layer of fines is on the bottom next to the base plate. After placement of each layer, evenly distribute the large aggregates in the layer and lightly spade its periphery with a spatula. Repeat this process until all 4 layers have been placed in the mold, leaving a small amount of fines for the top of the sample. Place a disc of filter paper on top of the specimen. Insert the top bearing plate and grease its top surface with approximately 10 g. of ordinary gun grease. Place the 4" spacer on the bearing plate with the groove hole to the right.

C. Place the mold and base plate on the compactor table and fasten it in place. Install front of mold chuck and tighten the mold bolts.

D. Close valve "E" and move handle on valve "F" to "Load On". With the spacer in the alignment groove on the pressure head. Open valve "E" and allow pressure head to apply load to specimen. When vertical movement has stopped, the spacer may be released. Release load by moving valve "F" to "Load Off". When load is completely released, close valve "E", move valve "F" to center position and remove split rings from beneath mold.

E. Again, hold the 4" spacer in the alignment groove of the pressure head, open valve "E" and move valve "F" to "Load On". When vertical movement stops, the 4" spacer may be released. Apply angle by moving handle on valve "I" to "Angle On". To start gyration, simultaneously turn switch "M" to "On" and move valve "I" to "Angle Off".

F. When gyration has ended, turn switch "M" to "Off", set revolution counter to zero and move valve "F" to "Load Off". When pressure head has retracted, close valve "E".

G. Remove the front of the mold chuck, loosen the base plate and slide the mold and base plate slightly forward. Remove the circumferential bands from the mold and separate the mold. Remove the specimen from the base plate. Height and weight of the sample are recorded, and the specimen is ready for testing.

APPENDIX B - DENSITY VARIATIONS WITHIN STABILIZED SPECIMENS

This Appendix contains the data used to compare the density variations between the 8-inch and 12-inch high compacted specimens. The data were obtained by sawing (perpendicular to the height axis) cement stabilized specimens into about 2-inch high parts. The 12-inch high specimens were, therefore, divided into six parts (see Table B-1) and the 8-inch high specimens were divided into 4 parts (see Table B-2). The part numbers were numbered from the top down; thus, in Table B-1 parts 1 and 6 are the top and bottom respectively. The initial specimens (up to specimen No. 1246) were compacted using a Teflon impregnated ceramic lined mold.

TABLE B-1 - DENSITY VARIATION IN 12 IN. HIGH SPECIMENS

Samp. No.	Vert. Pres. (psi)	Gyr Ang (Deg.)	No. Reb.	Mold Moist. (%)	1	2	3	4	5	6	Mean Value	Std. Dev.
1208	150	4	100	2.0	142.2	136.7	132.2	130.6	135.0	142.0	136.4	7.7
1209	150	4	20	2.0	139.6	135.8	133.0	130.0	136.4	138.5	135.6	5.6
1210	250	2	100	2.0	138.7	135.8	132.1	132.7	136.4	140.8	136.1	5.3
1211	250	2	20	2.0	134.0	133.1	130.0	130.3	135.9	136.5	133.3	4.3
1212	150	2	20	2.0	135.6	134.3	131.4	130.3	133.5	137.4	133.8	4.2
1213	150	2	100	6.0	140.2	137.4	132.2	132.8	138.3	144.9	137.6	7.5
1214	150	2	20	6.0	138.4	134.7	133.3	132.1	139.3	139.8	136.3	5.2
1216	250	4	100	6.0	146.1	140.3	135.0	136.5	142.1	146.8	141.1	7.7
1217	200	3	50	6.0	144.5	139.6	133.5	133.1	138.4	144.6	139.0	8.0
1218	200	3	50	2.0	139.8	136.3	132.6	131.8	136.2	140.4	136.4	5.7
1219	250	4	20	6.0	143.6	140.0	135.1	134.5	139.6	142.8	139.3	6.0
1220	200	3	50	4.0	141.0	137.4	131.4	132.1	138.3	140.5	136.8	6.5
1221	200	2	50	4.0	138.6	135.9	132.1	129.2	136.3	139.3	135.2	6.2
1222	200	4	50	4.0	145.0	138.1	132.1	132.5	139.0	142.6	138.2	8.2
1223	200	3	20	4.0	139.9	134.3	129.8	130.8	136.1	138.3	134.9	6.4
1224	200	3	100	4.0	142.8	138.9	133.3	133.9	144.8	136.7	138.4	7.4
1225	200	3	50	4.0	144.6	140.2	136.5	136.2	140.2	144.4	140.4	5.8
1226	200	3	50	4.0	142.7	137.7	132.1	132.4	136.7	142.1	137.3	7.2
1227	150	3	50	4.0	139.6	137.8	131.4	131.7	135.8	141.6	136.3	6.6
1228	250	3	50	4.0	141.4	138.1	133.1	132.7	138.6	143.5	137.9	6.9
1247	200	2	20	6.0	137.9	136.3	131.3	133.8	136.1	139.1	135.8	4.5
1248	200	2	100	6.0	142.9	136.5	131.5	134.8	139.8	144.4	138.3	7.8
1249	200	4	20	6.0	144.4	138.8	134.2	131.7	137.8	143.5	138.4	7.9
1250	200	4	100	6.0	146.2	140.8	133.9	135.0	140.5	146.2	140.4	8.3
1253	200	4	20	2.0	137.2	133.7	130.4	129.8	133.2	136.1	133.4	4.7
1254	200	4	100	2.0	138.8	135.0	129.6	128.1	134.2	139.9	134.3	7.5
1255	200	2	100	2.0	137.3	133.5	129.9	130.3	133.7	137.8	133.8	5.3
1256	200	2	20	2.0	134.6	134.1	130.8	130.8	133.7	135.7	133.3	3.2

Analysis of Variance:

Within Treatment Standard Deviation -- 4.07 pcf.

Within Treatment Coefficient of Variation -- 3.0%

TABLE B-2 - DENSITY VARIATION IN 8 IN. HIGH SAMPLES

Samp. No.	Vert. Pres. (psi)	Gyr Ang (Deg.)	No. Rev	Mold Moist. (%)	Density of Sections 1	2	3	4	Mean Value	Std. Dev.
1276	100	4	10	6.0	137.7	134.7	136.8	138.4	136.9	2.0
1277	300	4	30	6.0	142.2	143.4	144.4	145.4	143.8	1.7
1278	300	2	10	6.0	138.1	137.3	136.6	139.6	137.9	1.6
1279	100	2	30	6.0	135.3	136.3	136.2	138.1	136.5	1.5
1280	100	2	10	2.0	131.4	133.3	133.4	133.2	132.8	1.2
1281	300	2	30	2.0	137.5	138.3	139.0	139.1	138.5	0.9
1282	300	4	10	2.0	138.6	139.9	139.2	141.3	139.8	1.4
1283	100	4	30	2.0	137.8	134.5	133.8	138.1	136.0	2.7
1284	300	4	10	6.0	140.5	139.9	140.9	140.2	140.4	0.6
1285	100	4	30	6.0	139.6	137.4	136.4	141.8	138.8	3.0
1286	100	2	10	6.0	133.3	134.0	133.7	133.9	133.7	0.4
1287	300	2	30	6.0	138.4	139.7	140.3	140.8	139.8	1.3
1288	300	2	10	2.0	134.5	134.0	134.3	136.6	134.8	1.5
1289	100	2	30	2.0	133.9	134.4	135.6	136.3	135.0	1.4
1290	100	4	10	2.0	134.0	135.2	133.2	135.8	134.6	1.4
1291	300	4	30	2.0	141.0	140.2	140.1	142.2	140.9	1.2

Analysis of Variance:

Within Treatment Standar Deviation -- 1.31 pcf.

Within Treatment Coefficient of Variation -- 1.0%.

APPENDIX C - TEST RESULTS USED TO DETERMINE COMPACTOR CAPABILITIES

This Appendix contains the data used to determine the capability of the compactor to produce specimens of various moisture contents and densities suitable for testing. Replication errors and the equations for moisture content were determined from the data given in Table C-1. Estimates based on the equations given in Section 5 are also shown in this table. Replication errors for unconfined compressive strength and per cent strain were determined from the data given in Table C-2.

TABLE C-1 - MOISTURE CONTENT AND DENSITY OF COMPACTED SPECIMENS

SPECIMEN	GYRATORY ANGLE	VERT PRESS	REVS	MOISTURE CONTENT MOLD	MOISTURE CONTENT MEAS	MOISTURE CONTENT CALC	WET DENSITY MEAS	WET DENSITY CALC
1417	3	200	30	6.00	5.48	5.49	149.0	148.4
1418	3	200	30	2.00	1.91	1.94	138.4	138.5
1419	3	200	30	4.00	3.84	3.77	141.0	141.2
1420	3	200	30	2.00	1.92	1.94	139.3	138.5
1421	3	200	30	6.00	5.55	5.49	148.3	148.4
1422	3	200	30	4.00	3.82	3.77	139.8	141.2
1423	3	200	30	3.00	2.82	2.87	140.4	139.4
1424	3	200	30	1.00	0.91	0.99	137.5	138.2
1425	3	200	30	5.00	4.69	4.65	144.7	144.1
1426	3	200	30	1.00	0.91	0.99	138.0	138.2
1427	3	200	30	3.00	2.81	2.87	139.4	139.4
1428	3	200	30	5.00	4.79	4.65	144.2	144.1
1430	3	200	30	0.0	0.0	0.0	140.4	138.1
1432	3	200	30	3.00	2.89	2.87	139.4	139.4
1433	3	200	30	1.00	0.91	0.99	137.8	138.2
1434	3	200	30	4.00	3.85	3.77	141.0	141.2
1435	3	200	30	6.00	5.53	5.49	149.5	148.4
1436	3	200	30	2.00	2.01	1.94	139.1	138.5
1438	3	300	30	1.00	0.95	0.99	140.0	139.5
1439	3	300	30	6.00	5.46	5.49	149.8	150.2
1440	3	300	30	2.00	1.92	1.94	139.9	140.0
1441	3	300	30	3.00	2.86	2.87	141.4	140.9
1442	3	300	30	4.00	3.83	3.77	142.0	142.8
1443	3	300	30	5.00	4.79	4.65	146.4	145.8
1447	3	100	30	2.00	1.90	1.94	136.7	136.0
1449	3	100	30	3.00	2.86	2.87	135.9	136.7
1451	3	100	30	1.00	0.94	0.99	135.6	135.8

TABLE C-1 (CONTINUED)

SPECIMEN	GYRATORY ANGLE	VERT PRESS	REVS	MOISTURE CONTENT MOLD	MOISTURE CONTENT MEAS	MOISTURE CONTENT CALC	WET DENSITY MEAS	WET DENSITY CALC
1453	3	100	30	1.00	0.93	0.99	135.2	135.8
1454	3	100	30	6.00	5.62	5.49	147.4	145.4
1456	3	100	30	5.00	4.80	4.65	142.9	141.2
1457	3	100	30	4.00	3.79	3.77	138.8	138.4
1458	3	100	30	2.00	1.96	1.94	136.0	136.0
1460	3	100	30	3.00	2.85	2.87	137.3	136.7
1466	3	200	50	3.00	2.89	2.87	141.0	140.6
1467	3	200	50	2.00	1.95	1.94	140.3	139.6
1468	3	200	50	1.00	0.90	0.99	139.3	139.2
1474	3	200	50	3.00	2.85	2.87	141.0	140.6
1475	3	200	50	5.00	4.84	4.65	145.4	145.4
1476	3	200	50	4.00	3.72	3.77	141.8	142.4
1477	3	200	50	1.00	0.88	0.99	139.4	139.2
1478	3	200	50	2.00	1.86	1.94	139.9	139.6
1481	3	200	50	0.0	0.0	0.0	140.5	139.1
1483	3	200	10	3.00	2.85	2.87	138.1	136.9
1484	3	200	10	2.00	1.98	1.94	136.4	136.1
1485	3	200	10	1.00	0.97	0.99	136.0	135.9
1487	3	200	10	5.00	4.77	4.65	142.0	141.3
1490	3	200	10	0.0	0.0	0.0	136.2	136.0
1492	3	200	10	5.00	4.58	4.65	142.2	141.3
1493	3	200	10	6.00	5.54	5.49	145.4	145.5
1494	3	200	10	2.00	1.85	1.94	137.1	136.1
1495	3	200	10	3.00	2.80	2.87	137.3	136.9
1496	3	200	10	4.00	3.75	3.77	137.9	138.5
1498	3	200	10	6.00	5.64	5.49	145.2	145.5
1499	3	200	10	3.00	2.97	2.87	137.3	136.9

TABLE C-1 (CONTINUED)

SPECIMEN	GYRATORY ANGLE	VERT PRESS	REVS	MOISTURE CONTENT MOLD	MOISTURE CONTENT MEAS	MOISTURE CONTENT CALC	WET DENSITY MEAS	WET DENSITY CALC
1500	3	200	10	5.00	4.57	4.65	140.7	141.3
1501	3	200	10	1.00	0.97	0.99	137.0	135.9
1502	3	200	10	2.00	1.95	1.94	137.0	136.1
1505	3	200	10	0.0	0.0	0.0	135.8	136.0
1506	3	200	10	4.00	3.88	3.77	137.6	138.5
1507	3	200	10	6.00	5.52	5.49	145.3	145.5
1508	3	200	10	1.00	0.99	0.99	136.9	135.9
1510	3	200	10	4.00	3.78	3.77	137.2	138.5
1512	3	200	10	0.0	0.0	0.0	136.3	136.0
1513	3	200	30	5.00	4.78	4.65	145.3	144.1
1515	3	200	50	5.00	4.72	4.65	146.5	145.4
1516	3	200	50	3.00	2.96	2.87	140.5	140.6
1517	3	200	50	6.00	5.17	5.49	150.0	149.8
1518	3	200	50	1.00	0.95	0.99	138.6	139.2
1519	3	200	50	4.00	3.93	3.77	142.7	142.4
1520	3	200	50	2.00	2.00	1.94	140.1	139.6
1523	3	200	50	6.00	5.28	5.49	150.7	149.8
1524	3	200	50	4.00	3.93	3.77	143.2	142.4
1526	3	200	50	6.00	5.51	5.49	150.0	149.8
1527	3	200	50	0.0	0.0	0.0	140.1	139.1
1530	3	100	30	2.00	1.95	1.94	135.9	136.0
1531	3	100	30	4.00	3.85	3.77	137.4	138.4
1532	3	100	30	6.00	5.72	5.49	147.1	145.4
1533	3	100	30	5.00	4.83	4.65	142.6	141.2
1534	3	100	30	1.00	0.97	0.99	135.7	135.8
1537	3	100	30	4.00	3.82	3.77	137.5	138.4
1538	3	100	30	5.00	5.00	4.65	143.5	141.2

TABLE C-1 (CONTINUED)

SPECIMEN	GYRATORY ANGLE	VERT PRESS	REVS	MOISTURE CONTENT MOLD	MEAS	CALC	WET DENSITY MEAS	CALC
1542	3	300	30	5.00	4.78	4.65	147.1	145.8
1543	3	300	30	4.00	3.89	3.77	143.3	142.8
1545	3	300	30	3.00	2.93	2.87	141.2	140.9
1546	3	300	30	1.00	1.07	0.99	139.5	139.5
1547	3	300	30	2.00	2.03	1.94	140.7	140.0
1550	3	300	30	1.00	1.06	0.99	139.4	139.5
1551	3	300	30	2.00	1.90	1.94	140.5	140.0
1553	3	300	30	3.00	2.87	2.87	142.2	140.9
1554	3	300	30	4.00	3.79	3.77	143.5	142.8
1557	3	100	30	3.00	2.89	2.87	137.3	136.7
1558	3	100	30	6.00	5.59	5.49	146.1	145.4
1563	4	200	30	2.00	1.91	1.94	139.2	139.7
1565	4	200	30	4.00	3.81	3.77	141.9	142.5
1566	4	200	30	1.00	0.98	0.99	138.8	139.3
1569	4	200	30	0.0	0.09	0.0	138.9	139.1
1574	2	200	30	3.00	2.91	2.87	138.2	137.7
1581	4	200	30	2.00	1.82	1.94	140.4	139.7
1582	4	200	30	1.00	0.90	0.99	140.2	139.3
1583	4	200	30	0.0	0.02	0.0	138.0	139.1
1584	3	300	30	6.00	5.29	5.49	151.9	150.2
1585	3	300	30	5.00	4.75	4.65	147.9	145.8
1591	4	200	30	1.00	0.99	0.99	139.9	139.3
1594	4	200	30	4.00	3.80	3.77	142.3	142.5
1597	4	200	30	6.00	5.38	5.49	149.6	149.9
1602	2	200	30	6.00	5.46	5.49	145.9	146.4
1604	2	200	30	1.00	0.84	0.99	136.8	136.6
1606	2	200	30	3.00	2.83	2.87	138.0	137.7

TABLE C-1 (CONTINUED)

SPECIMEN	GYRATORY ANGLE	VERT PRESS	REVS	MOISTURE CONTENT MOLD	MOISTURE CONTENT MEAS	MOISTURE CONTENT CALC	WET DENSITY MEAS	WET DENSITY CALC
1607	2	200	30	4.00	3.71	3.77	137.5	139.3
1616	3	200	50	5.00	4.70	4.65	145.7	145.4
1622	4	200	30	6.00	5.33	5.49	149.8	149.9
1628	4	200	30	0.0	0.04	0.0	138.1	139.1
1634	4	200	30	2.00	1.76	1.94	139.0	139.7
1637	2	200	30	1.00	0.84	0.99	135.9	136.6
1638	2	200	30	2.00	1.82	1.94	136.7	136.8
1639	2	200	30	3.00	2.73	2.87	137.7	137.7
1640	2	200	30	4.00	3.72	3.77	138.3	139.3
1641	3	200	30	0.0	0.10	0.0	139.2	138.1
1642	3	200	30	0.0	0.05	0.0	138.4	138.1
1646	2	200	30	6.00	5.40	5.49	147.5	146.4
1649	3	300	30	6.00	5.00	5.49	149.8	150.2
1654	2	200	30	1.00	0.75	0.99	137.4	136.6
1657	4	200	30	6.00	4.99	5.49	149.1	149.9
1659	4	200	30	4.00	3.54	3.77	141.2	142.5
1669	4	200	30	3.00	2.89	2.87	140.4	140.6
1671	4	200	30	5.00	4.64	4.65	146.0	145.4
1673	2	200	30	0.0	0.15	0.0	136.8	136.6
1679	4	200	30	3.00	2.91	2.87	139.9	140.6
1682	3	200	50	0.0	0.06	0.0	138.1	139.1
1685	2	200	30	5.00	4.73	4.65	141.8	142.2
1686	4	200	30	5.00	4.69	4.65	146.0	145.4
1687	4	200	30	5.00	4.68	4.65	145.9	145.4
1688	4	200	30	3.00	2.83	2.87	141.3	140.6
1689	2	200	30	2.00	1.85	1.94	137.9	136.8
1691	2	200	30	4.00	3.71	3.77	138.0	139.3

TABLE C-1 (CONTINUED)

SPECIMEN	GYRATORY ANGLE	VERT PRESS	REVS	MOISTURE CONTENT MOLD	MOISTURE CONTENT MEAS	MOISTURE CONTENT CALC	WET DENSITY MEAS	WET DENSITY CALC
1692	2	200	30	6.00	5.62	5.49	145.5	146.4
1693	2	200	30	0.0	0.05	0.0	136.5	136.6
1695	2	200	30	2.00	1.84	1.94	137.2	136.8
1696	2	200	30	5.00	4.68	4.65	143.4	142.2
1697	2	200	30	5.00	4.69	4.65	143.1	142.2
1699	2	200	30	0.0	0.10	0.0	136.1	136.6
1705	4	300	50	1.00	1.02	0.99	139.6	141.7
1706	4	300	50	3.00	2.89	2.87	142.5	143.3
1714	2	300	50	1.00	0.99	0.99	137.9	139.0
1715	2	300	50	3.00	2.97	2.87	140.3	140.4
1719	2	100	10	5.00	4.73	4.65	134.8	136.5
1723	4	300	50	5.00	4.70	4.65	148.6	148.4
1724	4	100	50	1.00	0.89	0.99	136.6	137.9
1726	4	100	50	5.00	4.59	4.65	142.9	143.8
1727	2	300	50	5.00	4.62	4.65	145.0	145.2
1728	4	300	10	1.00	0.88	0.99	137.5	138.4
1730	4	300	10	5.00	4.65	4.65	143.6	144.4
1731	4	300	10	3.00	3.05	2.87	139.6	139.7
1732	4	100	50	3.00	3.08	2.87	137.5	139.1
1733	2	100	10	1.00	1.19	0.99	131.1	132.0
1734	2	100	10	3.00	3.09	2.87	132.4	132.5
1738	4	300	50	2.00	1.63	1.94	142.2	142.2
1740	4	300	50	6.00	5.15	5.49	151.5	153.0
1742	2	100	10	4.00	3.89	3.77	132.3	133.9
1744	2	300	50	2.00	1.89	1.94	139.7	139.4
1748	4	300	10	4.00	3.81	3.77	141.5	141.5
1755	4	300	10	6.00	5.85	5.49	147.2	148.8

TABLE C-1 (CONTINUED)

SPECIMEN	GYRATORY ANGLE	VERT PRESS	REVS	MOISTURE CONTENT MOLD	MOISTURE CONTENT MEAS	MOISTURE CONTENT CALC	WET DENSITY MEAS	WET DENSITY CALC
1757	2	300	50	4.00	3.84	3.77	140.1	142.2
1758	2	300	50	6.00	5.36	5.49	145.5	149.6
1759	4	300	50	4.00	3.71	3.77	143.9	145.3
1763	2	100	10	6.00	5.54	5.49	139.7	140.5
1765	4	300	10	2.00	1.84	1.94	138.3	138.8
1767	4	100	50	2.00	1.84	1.94	137.4	138.2
1768	4	100	50	4.00	3.73	3.77	139.0	140.9
1769	4	100	50	6.00	4.61	5.49	146.6	148.1
1770	2	100	10	2.00	2.04	1.94	131.0	132.0

Moisture Content Analysis of Variance:
Within Treatment Standard Deviation--0.08%
Within Treatment Coefficient of Variation--2.7%

Wet Density Analysis of Variance:
Within Treatment Standard Deviation--0.33 pcf
Within Treatment Coefficient of Variation--0.23%

TABLE C-2 - RESULTS OF UNCONFINED COMPRESSION TEST ON REPLICATE SPECIMENS

Treat. No.	Vert. Press. (psi)	No. Rev	Gyr Angle (Degrees)	Mold Moist. (%)	Comp Str (psi)	Mean Value	Std. Dev.	Percent Strain	Mean Value	Std. Dev.
					29.4			0.74		
1	100	10	1	2	29.9	28.9	1.4	0.86	0.82	0.07
					27.3			0.86		
					16.3			0.99		
2	100	10	1	6	24.3	18.5	6.5	0.97	0.98	0.01
					15.1			0.98		
					75.8			1.23		
3	200	30	2	2	66.1	71.2	1.7	1.35	1.23	0.13
					71.6			1.10		
					38.1			1.09		
4	200	30	2	6	30.5	33.5	4.0	0.96	1.04	0.07
					32.0			1.08		
					92.1			0.99		
5	300	50	1	2	98.8	96.7	3.9	0.86	0.86	0.13
					99.0			0.74		
					79.5			1.00		
6	300	50	1	4	86.1	88.8	12.7	1.00	0.96	0.24
					100.6			0.87		
					37.0			1.37		
7	300	50	1	6	50.3	37.6	12.4	1.00	1.24	0.21
					25.5			1.34		

Compressive Strength Analysis of Variance:
Within Treatment Standard Deviation -- 7.10 psi.
Within Treatment Coefficient of Variation -- 13.3%

Per cent Strain Analysis of Variance:
Within Treatment Standard Deviation -- 0.113%.
Within Treatment Coefficient of Variation -- 11.1%

APPENDIX D - REGRESSION TECHNIQUE USED FOR DENSITY EQUATION

Often in the analysis of research data, it becomes desirable to utilize non-linear mathematical models to represent data. Such models usually require special treatment because there is no generally applicable solution for handling non-linear regressions, nor are there existing general computer programs for such use. The model selected in the analysis of the density data reported in Section 4 was of this type because it contained some non-linear regression constants. The authors believe that the technique used may be of some general interest because many non-linear regressions could be solved in a similar manner.

As may be varified by inspection of equation 2, the model used was of the following form:

$$Y = A_0 + A_1 X_1^3 + A_2 Q + A_3 X_1 Q$$

Where Y = Dependent Variable

$Q = \log_e (X_2 X_3^{B_1} X_4^{B_2})$

X_1, X_2, X_3, X_4 = Independent variables

A_0, A_1, A_2, A_3 = Linear regression constants

β_1, β_2 = Non-linear regression constants

The criterion for solving the regression constants is the same as that used for a standard linear regression which minimizes the mean squared error which occurs when

$$\frac{1}{m} \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2 = \text{Minimum value}$$

where y_i = i^{th} of n observations of the dependent variable, Y.

$\hat{Y}_i$ = Estimated value of Y_i from model.

m = n - number of regression constants.

The procedure used for evaluating the regression constants was first to select arbitrarily three different values for β_1, centered around its expected approximate value. Similarly, three values were selected for β_2. There are 9 possible combinations of the three values for each of the two β's. For each of the 9 combinations the mean squared error was found using a standard linear, multiple regression computer program. A second degree response surface was then used to relate the β's to the mean squared error. Again a standard linear multiple regression computer program was used to determine the best fit for the response surface. The data for this second regression were the 9 mean squared errors (dependent variable) and the corresponding sets of β's (independent variables). The partial derivative of the response surface equation with respect to β_1 gives a linear equation in the two β's. Differentiating with respect to β_2 results in an additional linear equation in the two β's. Differentiating with respect to β_2 results in an additional linear equation in the two β's. The resulting set of simultaneous equations were then solved for new estimates of the approximate values for the β's. The process can be repeated over and over again until the changes in the β's become as small as desired.

Table D-1 contains the successive central trial values used in the determination of the non-linear regression constants reported in Chapter 4. The three trial values used in an iteration for β_i were $\beta_i - R_i$, β_i, and $\beta_i + R_i$ (i = 1 or 2). Convergence was assumed when the changes in the central values of the β's became less than 0.001.

After suitable values for the β's are found, they are used in the original model to determine the linear regression constants.

TABLE D-1 - SUCCESSIVE VALUES OF NON-LINEAR REGRESSION CONSTANTS

Iteration	β_1	β_2	R_1	R_2	Mean Squared Error
0	1.0000	1.0000	.5000	.5000	1.23146
1	1.5103	1.6880	.2500	.3654	.92601
2	1.6759	1.8756	.1250	.1700	.91455
3	1.6844	1.8890	.0625	.0825	.91454
4	1.6825	1.8867	.0313	.0412	.91454
5	1.6813	1.8856	.0156	.0206	.91454
6	1.6810*	1.8853*			.91454

* Convergence criterion met.