LABORATORY COMPACTION OF A
SILTY CLAY TO SIMULATE FIELD
DENSITY CURVES

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SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
JUNE, 1956

Signatures of Authors ____________

Department of Civil and Sanitary Engineering, May 21, 1956

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Abstract

of a thesis entitled

LABORATORY COMPACTION OF A SILTY CLAY TO SIMULATE FIELD DENSITY CURVES

by

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and

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Submitted in partial fulfillment of
the requirements for the degree of
Master of Science in the Department
of Civil and Sanitary Engineering on
May 21, 1956

One of the most popular methods of soil stabilization used in present day construction is compaction. The meaning of the term compaction as defined by the authors for the purposes of this study is, "That process by which the volume of a given mass of soil is reduced through the physical application of an external force".

Methods for designing and controlling the compactive effort for a given job in currently acceptable practice leave much to be desired. The most desirable method, which requires construction, testing, and analysis of a test embankment, is very expensive. Cheaper methods in which use is made of experience, judgment, comparison, and results of laboratory test data are not within the usually desired limits of accuracy.

The need for accurately reproducing field conditions in the laboratory becomes immediately apparent. If samples, in which stress strain and strength characteristics are equivalent to those obtained in the field could be manufactured in the laboratory, the need for a test embankment would be eliminated, and design would be accurate. This then should be the goal of any research which strives to improve present laboratory compaction methods.

Good field data for the necessary comparisons which must be made in any such study are extremely limited. However, moisture - density relationships, CBR, and Triaxial test data are available for large scale field tests conducted on two soils by the U. S. Waterways Experiment Station, Vicksburg, Mississippi. Current research on the problem is therefore limited to these two soils. One of these, a lean silty clay from a zone of weathered loess in the vicinity of Vicksburg, Mississippi was chosen for this investigation.

Eng'g. (C.E.) Aug. 23, 1956

Since time did not permit a thorough investigation of comparative stress-strain characteristics of the soil, this study was limited to an attempt to reproduce, by laboratory methods, the moisture density relationships obtained in the field test. The authors felt that this was a good starting point for a larger investigation. This feeling is based on the assumption that if laboratory prepared samples follow the same moisture density relationships as those obtained in the field, they will also essentially follow the same stress-strain and strength relationships. Since the establishment of moisture - density relationships in the laboratory is cheaper in terms of time, this becomes the logical starting point for the general research indicated above.

The investigation consisted of three phases. In phase 1, a compaction machine was designed and constructed. The machine was designed to reproduce as closely as possible, within the limits of economy and practicality, the action of a typical rubber tired roller. Phase 2 consisted of studying the performance of this machine under different basic conditions or variables. In phase 3, an effort was made to reproduce (with the machine) a moisture density curve formulated in the Vicksburg field test. The aim of phase 3 was not simply to reproduce the curve, but to do so by using variables on the machine which could be easily correlated with unit pressure, number of coverages, number of lifts, and time rate of application of pressure used in the field test.

Results of phase 3 showed that with the same unit pressure, same number of coverages and lifts, and the same time rate of application of pressure, the laboratory machine could essentially reproduce the field curve. It is therefore concluded that this approach to the general problem shows promise of validity, and that research along these lines should continue with the examination of stress-strain relationships for this soil and for other soils.

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Cambridge, Massachusetts
May 21, 1956

Professor L. F. Hamilton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, this thesis entitled "Laboratory Compaction of a Silty Clay to Simulate Field Density Curves" is submitted.

Respectfully yours,

Edward C. West

Harry M. Coyle

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the many people whose kindness, patience, time, and advice helped immeasurably in pursuing this study.

We are especially indebted to Mr. C. M. Stahle for the contribution of many ideas for the design of the machine, and for the construction thereof.

The authors also wish to thank the following members of the Soil Mechanics staff: Professor H. P. Aldrich for his advice, guidance, and suggestions during the entire investigation; Professor D. W. Taylor for his encouragement before his untimely death; Professor T. W. Lambe for his interest and suggestions; and Mr. J. M. Roberts for his comments during the course of study.

Further gratitude is expressed for the diligence with which the Misses Mary de Sesa and Theresa Di Prizio typed the manuscript.

Acknowledgement is also made of the cooperation of the Waterways Experiment Station, Vicksburg, Mississippi, for providing the soil and a great deal of necessary field data. Col. A. P. Rollins, Commanding Officer of the Experiment Station, and Mr. W. J. Turnbull, Chief of the Soils Division were most helpful in this regard.

E. C. West

H. M. Coyle

TO OUR WIVES

FOR THEIR EVERLASTING

PATIENCE, FOREBEARANCE

AND STRONG MORAL SUPPORT.

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CHAPTER I INTRODUCTION

Among the fundamental problems which face foundation engineers is the enigma of developing or exploiting the basic engineering properties of their most important material, soil. Probably the most universal method of developing soil properties for a given job is compaction. Compaction is defined as reducing the volume of a given mass of soil by the application of an external physical force. Although a great deal of study has been devoted to the subject of compaction, many of its more important secrets remain obscure and not completely understood.

The designer of an earth embankment today is torn between the cost of his design and the accuracy thereof. To get an accurate, dependable measure of the compaction characteristics of a soil or soils chosen for a given job, it is necessary to construct a test embankment. Tests are then run on samples from this embankment, and analysis of the test results along with sound application of judgment and experience give the engineer a solid basis for his design. This process is often out of the question because of its prohibitive cost, yet this is the only really reliable method available. The alternative is to resort to judgment, experience, comparison, laboratory tests, and combinations of these. This second alternative is not within the usually desired limits of accuracy, and often leads to erroneous conclusions, uneconomical or dangerous designs and legal disputes (Ref. #5).

Research into the mysteries of compaction has given the engineer a fairly good idea on how such basic properties as density, moisture content, permeability, shear strength, and C B R vary with compactive effort. The primary difficulty with which the engineer is faced is his inability to correlate laboratory tests with results in the field. Present methods of compacting samples in the laboratory are completely arbitrary and empirical. The ideal solution to this very vital problem is a laboratory process which reproduces the action of field compactors. More important, this process should also produce in the soil the same stress-strain and strength characteristics as those induced by field equipment.

Analysis of the problem outlined above starts with the hypothesis, "The same compactive effort applied to samples of the same soil under similar conditions will yield equal results". This hypothesis can be accepted with little reservation. From this it follows that the laboratory compaction apparatus should reproduce the action of the field equipment as closely as possible consistent with economy and practical considerations. It is readily recognized that exact reproduction is impossible if the usual advantages of laboratory work are to be preserved. The problem now resolves itself into one of reproducing those items which can be reproduced and correlating those items which are impossible to reproduce because of normal limitations imposed by the laboratory.

An inherent difficulty in research of this nature is the woeful lack of good field data with which to make the necessary comparisons. Choice of soil and field equipment with which to compare the laboratory work is therefore limited. The United States Waterways Experiment Station at Vicksburg, Mississippi has conducted extensive field tests on two soils native to that area. One of these soils, a lean silty clay from a zone of weathered loess in the vicinity of Vicksburg, was chosen for this investigation. 1000 pounds of the subject soil was subsequently procured for the study.

Because of the intricacy of the general problem presented above, the veritable mountain of work required to investigate such a problem, and the limited time available for this thesis, it became vitally necessary to limit the objectives of this study at the outset. The study was first confined to an investigation of the rubber tired roller since this particular field compactor is fast becoming the most popular method of compacting soils in current construction practice. It was then decided to attempt reproduction of moisture density curves rather than stress strain relationships per se. Adequate data to substantiate conclusions on the latter would have been impossible of attainment in the available time, and moisture density relationships were considered a good index to all of the important soil properties involved. The objective of this study then is to produce moisture density curves by laboratory methods meeting the following specifications:

1. Curves are to lie within the band of scattered points obtained by typical rubber tired rollers compacting the subject soil under field conditions.
2. Physical variables such as coverages, layers, unit pressure, and time rate of application of pressure are to be the same in the laboratory as those used in the field or at least possible of accurate correlation.

To accomplish this objective, the investigation was divided into three phases which are described briefly in the following paragraphs.

Phase 1 - A detailed study was made of current laboratory compaction methods with emphasis on their advantages and limitations. Special attention was devoted to the work of Wilson with his "Miniature Compaction Device (Ref. #25), and Osterberg and Rutledge's work on the "Kneading Compactor (Ref. #11). A laboratory compaction machine combining the ideas of Wilson, Osterberg, and Rutledge along with some original thoughts of the authors was then designed and constructed.

Phase 2 - This phase consisted of studying the action of the compaction machine with special regard to reproducibility of results and performance under varying conditions of pressure, lift thickness, number of coverages, time rate of application of pressure, and mold size. The machine proved to give consistent results with minimum scatter of points on any given curve. Daily use showed the machine to be rugged and readily adaptable to the changing conditions just described. Test results showed a normal reaction to increase and decrease of compactive effort. Satisfied with the performance of the machine the authors then embarked on phase 3 of the study.

Phase 3 - This phase was devoted to reproducing (with the laboratory apparatus) a curve obtained in the field at Vicksburg with a rubber tired roller. It should be pointed out here that this field curve is an average of many scattered points. It is the best criteria on which to base a study of this nature, but the reader should be cautioned that it represents an area or range rather than a well-defined curve. The end result of phase 3 was a laboratory curve which came within 0.5 $\#/ft^3$ of maximum field density 1.4 % of optimum field water content, and 4 % of saturation on the wet side of the field curve. Further efforts to move the wet side of the curve closer to field saturation succeeded in suggesting several promising possibilities. Various special density studies were conducted to investigate these possibilities but insufficient data was obtained for drawing any firm conclusions. The curve indicated above was obtained with the same unit pressure, number of coverages, number of layers, and time rate of application of pressure as used in the field test. This last fact is considered to be most significant.

The overall conclusion arising from this study is that this method of laboratory compaction shows promise of validity. Research along these lines should therefore be continued with special emphasis on examining stress-strain and strength characteristics of samples compacted with the machine used in this study. Similar studies should also be initiated on other soils for which the necessary field data are available.

CHAPTER II BACKROUND

Before launching into a discussion of the details of this particular investigation, it is necessary to review work which has already been done in the compaction field. This must be done in order to place this study in its proper perspective.

A. Purpose of Compaction.

The general purpose of compaction in the field is to improve, develop, or otherwise tailor certain properties of the soil to suit the peculiar needs of a given project. These properties may be one or more of the following: strength, permeability, and compressibility. This is most commonly accomplished in the field with rollers of various types, vibration, pneumatic tamping devices, etc.

B. Use of Laboratory Compaction.

Laboratory compaction is useful in three general areas: design, control of construction, and research.

1. Design - In preliminary studies, especially where test embankments are not resorted to, representative samples of soil to be used in the project are compacted in the laboratory in order to study physical properties of the soil. These data along with results from other common laboratory tests are used by the designer.

2. Field Control - Once design is complete, laboratory compaction becomes one of the most frequently used methods for field control. From standard laboratory tests, optimum dry densities and optimum water contents are obtained. The specifications for compaction will often be based on this information. Usually the specifications will require a given compactive effort for a given range of water contents or that a given per centage of maximum dry density be attained in the field. These items are supposed to be

checked frequently by inspectors on the job.

3. Research - Samples compacted by laboratory methods are used in studying permeability, strength, compressibility, etc., on a qualitative and/or quantitative basis.

C. Resumé of Laboratory Compaction Methods in Use Today.

These tests are described briefly in order that the reader be in a position to evaluate the differences between the machine used in this study and other common laboratory techniques. The list of compaction machines does not puport to be all inclusive, but is rather a survey of the more well-known methods.

Laboratory compaction had its real start in 1933 when R. R. Proctor developed the "Standard Proctor" (or Standard AASHO) test in connection with the construction of earth fills in California (Ref. #8 & 14). This test is an impact test in which a hammer falls freely and strikes soil in a mold. The "Modified Proctor" (or Modified AASHO) was developed by the U. S. Army Corps of Engineers to give a heavier standard of compaction for air field construction (Ref. #8). This test uses the standard CBR mold in order that CBR tests can be conveniently run directly on compacted samples. The test is fundamentally the same as the Standard AASHO. The "British Standard" compaction test is the same as the"Standard AASHO" with the exception that the British remove all material retained on the 3/4" sieve; whereas in the United States, that fraction retained on the 3/16" is scalped. (Ref. #3). The chart below gives vital particulars on the two so-called AASHO Tests.

	Mold Size	# of Layers	# of Blows per Layer	Hammer wt	Ht of Fall of Hammer	Compactive Effort
Standard AASHO	4.6" X 4" Diameter	3	25	5.5#	12"	12,400 $\frac{\text{FT\#}}{\text{FT}^3}$
Modified AASHO	5 ± in X 6" Diameter	5	55	10#	18"	56,000 $\frac{\text{FT\#}}{\text{FT}^3}$

The "Providence Vibrated" test, although not standardized at present, is receiving increasing attention in areas where granular soils are prevalent. This test was developed by K. S. Lane in 1942 to obtain higher compaction standards on cohesionless soils (Ref. #3). Another of Lane's goals was to obtain laboratory compaction values more closely approximating field values. In this test, the compaction mold (7" diam.) is welded to a base plate. A dry sample of known weight is placed in the mold under a surcharge of 1000# imposed by a calibrated spring. A 2-1/2# hammer is then used to strike the outside of the mold until change in height of the sample ceases. The height of sample is then measured and volume is computed. It is then a simple matter to obtain the dry density. This method does in fact give higher densities for laboratory compaction, and these densities are consistent with those obtained in the field. The primary factors blocking standardization of this test are:

1. The mold changes shape and volume under constant beating and must be recalibrated or replaced frequently to maintain accuracy and uniformity of results.

2. Since the beating is done by hand, there is little uniformity in time rate of application of the blows and coverages around the circumference of the mold.

The New England Division, Corps of Engineers, is presently working on means to eliminate the above-mentioned difficulties. They are applying blows automatically on specially prepared gun metal molds.

The "California Static Load" (or Porter Static Load) test was developed in 1935 by O. J. Porter, California Division of Highways, in connection with the C B R test (Ref. # 3 and 13). The mold is 6" in diameter and 8" high with a detachable base plate. A 5" long piston fits into the mold. Material is scalped at the 3/4" sieve. Loading is static, and is accomplished by a hydraulic press. The customary maximum load is 2000 psi applied gradually under a controlled rate of strain equal to .05 $^{in}/_{min}$. Maximum pressure is maintained for one minute and released over a period of 20 seconds. Note that only one layer or lift of soil is used.

Thus far tests have been discussed which are in general use to varying degrees in current practice. Now let us review two tests which are later developements, and which were designed with the idea of reproducing the action of field equipment in the laboratory. The first of these is the "Harvard" (or Wilson) Miniature developed at Harvard University by S. D. Wilson and A. Casagrande (Ref. #25). The mold size is $^{1}/_{454}$ cu. ft. which means that the weight of a compacted specimen in grams is numerically equal to the unit weight in lb. per cu. ft. The mold is furnished with the customary detachable base and collar; and the equipment is accompanied by an extruding apparatus, and a jig for conveniently removing the collar. Unconfined compression tests can be run on samples without trimming because of the convenient dimensions chosen for the mold. The tamper is hand operated, and consists of a spring loaded piston 1/2" in diameter. The spring is prestressed to a given value by means of a lock nut on top of the tamper. The tamping operation consists of pushing the tamper into the soil until the load equals the prestress. This point is easily determined by noting that point at which the spring starts to deform under load. The tamping force, number of tamps, and number of layers can be varied to produce a wide range of compactive efforts. Note that the effort is more static than dynamic, and closely approximates the action of a typical sheepsfoot roller. The apparatus is limited to fine-grained soils because of the small mold used.

Results of tests on fine grained soils show that this device can reproduce field density curves very closely (Fig. C-10).

The second recent significant developement in laboratory compaction methods is the "Kneading Action" compactor developed by Osterberg and Rutledge at Northwestern University (Ref. #11). This machine can be used for so-called kneading compaction as well as for dynamic compaction. It was designed with the following objectives in mind: (1) Produce optimum water contents and maximum densities close enough to field results to be used for field control. (2) Produce moisture - density curves reasonably the same as those produced by field compaction equipment. (3) Produce soil samples having stress-strain and strength characteristics reasonably close to those of field compacted samples. These objectives are designed to overcome the discrepancies between field and laboratory compaction which are common in current practice. Limited test results on the machine show that the idea is feasible, and that the apparatus yields good results for the soils tested (Fig. C-10). Only the kneading compaction set-up is described here since impact or dynamic compaction with this machine is similar to the AASHO tests described above. The mold is a standard C B R mold 6" in diameter and 7" high. Compaction is produced by compressed air automatically such that pressure and time rate of application can be held steady and uniform. The compacting foot is a segment of a circle, slightly rounded on the bottom and attached to the piston through a spring loaded universal joint such that a slight rocking or kneading is induced by irregularities in the soil. The mold rotates automatically with each application of pressure such that a complete coverage is obtained after a specified number of tamps. Variables are: unit pressure, time rate of pressure application, number of lifts, number of coverages.

It is important here for the reader to have a clear understanding of basic differences between the C-W Kneading Compactor used in this study and the Northwestern Kneading Compactor described immediately above. The primary difference between the two is a matter of design perspective. The Northwestern device is fundamentally an automatic machine with the variables controlled by mechanical means. The C-W Compactor is completely hand operated, and since there is no firm mechanical control of the variables, human error is more pronounced. Due to its automatic features the Northwestern Compactor is more complex, more expensive, and larger than the C-W device. The details of applying compactive effort are basically the same in both machines, and one would therefore expect them to yield similar results. Fig. C-10 bears this out. It is believed that there is a place for both machines in practice, and the fact that they give similar results is fortunate. The Northwestern Compactor lends itself best to detailed research and to the permanent laboratory facility. The C-W Compactor is well-suited to the temporary field type laboratory.

A reader interested in the possible differences in kneading action between the two machines should compare the machines more closely than is possible with the meager information available to the authors at this time. The reader is referred to Chapter IV for a complete description of the C-W Kneading Compactor. Published description on the Northwestern Compactor gives insufficient information for determining whether or not the manner in which the foot kneads is indeed the same for both machines.

CHAPTER III THEORETICAL CONSIDERATIONS

Theoretical considerations are analyzed here on the basis of the hypothesis, "The same compactive effort applied to samples of the same soil under equal conditions will yield equal results." It is believed that this hypothesis can be accepted with little reservation. In order to reproduce field compaction in the laboratory, it follows that all conditions and factors involved must in turn be duplicated. The following analysis attempts to outline the variables concerned in terms of their effect on compaction and feasibility of reproducing them in the laboratory. The variables have been categorized to facilitate the discussion. It is recognized that many of these variables as outlined below overlap their category. To segment the problem any further however, is impossible due to the infinitely complex nature of the interrelation of all the factors concerned.

Let us first examine the various basic methods of delivering compactive effort. One method is dynamic or impact. Here a weight drops freely and strikes the soil with a sharp instantaneous blow. (Ref. #1). A second method is static compaction. In its purest sense static compaction is accomplished by a weight sitting on the soil without motion relative to the soil surface. (Ref. #1). A third basic method of compacting soil is by vibration. Here the soil mass is vibrated by an external force in such a manner that the soil particles rearrange themselves. In so doing, the particles tend to fill existing voids in the mass until some minimum volume is reached. The latter is not discussed any further since the method applies only to granular or non-cohesive materials, and therefore has no bearing on the problem at hand.

Rollers used in field compaction are neither purely dynamic or purely static in character. They are rather a combination of these two. To describe this action we adopt the term "Kneading Action" as used by Osterberg and Rutledge in their studies on this same subject (Ref. #11). At this point we can make our first conclusion. The laboratory apparatus must be of the "Kneading Action" type since neither dynamic or static compaction per se meets with the requirements of the hypothesis.

Now we shall examine the soil factors concerned. Soil is no doubt the biggest single variable. Among the many soil properties which have some bearing on the problem are: soil minerals, grain size distribution, Atterberg limits, specific gravity, shear strength, compressibility, permeability, moisture content, shape of particles, chemical content, and past history. To evaluate each one of the above-mentioned soil properties with relation to compaction is beyond the scope of this report. Research has shown how some of these properties are affected by compaction and vice versa (Ref. #17, 22, & 9). Theories have been presented for others, but an understanding of all the relationships involved has not yet been reached, nor is there likelihood of attaining such an understanding in the near future. We can, very blandly, point out that the exact same soil must be used in the laboratory to reproduce field data. Anyone familiar with soil mechanics knows that the ability to get samples alike in every respect is somewhat remote. Due to differences in past history, disturbance on excavating, processing in the laboratory, and the ever-to-be-expected variation of soil samples taken within several feet of one another in the same borrow area: we should expect to get some differences between field laboratory from one to another. This difficulty must be recognized from the start. It can not be overcome completely, but it can be minimized by judicious choice of samples, careful sampling techniques, extensive identification tests, and searching interpretation of test results.

There are other variables concerned which the authors classify as miscellaneous for want of a more descriptive term. These items generally arise from the physical factors attendant to the process of compaction and the circumstances under which compaction is accomplished. Most of these items can be controllled in the laboratory, and some of them can also be controlled in field work. These are the items which get the largest share of attention in this paper. Each of the so-called miscellaneous variables is listed below and discussed briefly:

1. Temperature and Relative Humidity - These items can be controlled in a laboratory, but can only be recorded in the field. Some measure of field control can be attained by choice of construction season where we can expect limited uniformity in conditions. In this study we are forced to the somewhat questionable assumption that temperature and relative humidity may be neglected. This assumption is adopted because of lack of field data and limited laboratory facilities.

2. Unit Pressure - The pressure per unit area can be controlled in the laboratory and in the field. Therefore the same unit pressure should be used in laboratory work as applies to the piece of field equipment in question.

3. Number of Coverages - Number of coverages is defined as the number of times that a given compactive effort is applied to the entire surface of a given lift. This also can be controlled in both field and laboratory work. It follows that coverages should be reproduced between the laboratory and the field.

4. Velocity of Impact - Velocity of impact is primarily a function of the type of compaction exerted. In static compaction velocity of impact is zero for all practical purposes; whereas in dynamics or impact compaction this velocity is a function of the height of fall and acceleration due to gravity. Since kneading compaction has been previously defined as a combination of static and dynamic, the velocity of impact for a typical field roller is greater than zero. If the roller does not bounce, velocity of impact is zero for all practical purposes. If on the other hand, bouncing does occur, the velocity of impact is increased to some small finite value. For an average bounce of 2 inches or less velocity of impact is on the order of 3 fps. However, the bouncing is not sufficiently uniform to be evaluated quantitatively. The machine is therefore best constructed with regard to impact velocity to provide random bouncing such as that which takes place in the field. With this feature incorporated, we shall then assume that velocity of impact is reproduced if the laboratory moisture density curve is essentially the same as the field curve. This assumption is reasonable since the maximum expected impact velocity is small in any event.

5. Time Rate of Application of Pressure - This is defined as the time increment for which the load is maintained in any given application of pressure. Time can be computed for the field if the length of the contact area and roller speed are known. It must be pointed out however, that this computed time is not exactly correct because the roller is bouncing. In the laboratory time can be easily measured and controlled. It is therefore possible to produce field time increments in the laboratory, if we accept field time as being adequately represented by length of the contact area divided by the roller speed. It

should also be mentioned here that the roller speed is not maintained absolutely constant. This fact affects our evaluation of time as well as velocity of impact treated in 4 above.

6. **Number or Thickness of Lifts** - Here a twofold effect must be examined. Generally speaking, the thinner the layer, the greater the effect of an application of pressure on that layer. Also if thinner layers are used, the compactive effort is transmitted to other layers below the layer being compacted. The magnitude of these effects can be measured in the field or in the laboratory by suitable instrumentation with strain gauges or the like. These magnitudes can also be computed within a reasonable margin of error by use of the Westergaard or Boussinesq analysis (Ref. #15). In correlating layer thickness in the laboratory with layer thickness in the field, any analysis of the transmission of pressure loses some of its meaning since the amount of pressure transmitted is also affected by such things as side friction and sample size. Since the problem of correlating the subject of layers between field and laboratory can be seen to depend on number of layers, thickness of each layer, sample size, side friction, etc; it is believed that an empirical approach to the solution of this problem is more practical than a direct analysis. This empirical approach consists of finding combinations of variables which yield laboratory curves within the band of scattered field points. In this study an effort is made to determine several of these combinations. When many of these combinations have been determined, it might then appear that they follow some logical pattern.

7. **Sample Size** - The volume of a laboratory sample is easily measured, but the corresponding volume of soil affected by field compaction is very difficult if not impossible to analyze. For this reason,

an empirical approach is once again thought to be the most practical method of analysis. This problem is intimately connected with the correlation of layers as seen in the discussion for 6 above.

8. Shape and Size of Contact Area - The shape and size of contact area in both field and laboratory are easily measured. It is impractical however, to use the same foot size or contact area in the laboratory as that which is used in the field. A contact area as large as that produced by a field roller would make the laboratory apparatus unwieldy, uneconomical, and consequently impractical.

We can now summarize the theoretical considerations presented above by using them to formulate guide specifications for the laboratory compaction apparatus, and by defining more closely the limits of this investigation. The guide specifications are listed below in two categories. The first category arises from arbitrary limitations imposed by available funds and materials for constructing the machine and by the authors' conception of certain necessary qualities that a good piece of laboratory apparatus should possess. This is followed by a second category of specifications based on the theory already presented. The reason for this order of presentation will become apparent as the reader digests category No. 1, and sees how it limits the application of theory.

CATEGORY NO. 1

a. Maximum use must be made of available scrap material since funds for the machine are limited to approximately 30 dollars.

b. The machine should possess the following basic characteristics;

(1) Simplicity

(2) Flexibility - Easily adapted for changing the basic variables in order to make an adequate empirical analysis.

(3) Durability - Rugged enough to withstand hard use.

(4) Adaptable for use in permanent or in temporary field laboratories.

(5) Easily operated by unskilled laboratory workers.

(6) Not so sensitive to human error that results cannot be readily duplicated by different operators.

CATEGORY NO. 2

a. Machine should be of the kneading action type, approximating as closely as possible the action of a typical rubber-tired roller.

b. Representative samples of the same soil as used in the field must be used in laboratory compaction.

c. Control of temperature and relative humidity is confined to testing in normal room conditions.

d. $Pr = \text{pressure ratio} = \dfrac{\text{laboratory unit pressure}}{\text{field unit pressure}}$

$= 1.$

e. $Cr = \text{coverages ratio} = \dfrac{\text{number of laboratory coverages}}{\text{number of field coverages}}$

$= 1$

f. It is assumed that velocity of impact may be neglected if true kneading action is indeed produced. This assumption is based partly on the feeling that the effect of velocity of impact in the narrow range pointed out previously is indeed negligible, and also on the practical impossibility of providing the necessary instrumentation and controls to reproduce velocities in the laboratory.

g. $Tr = \text{time ratio} = \dfrac{\text{time increment in the laboratory}}{\text{time increment in the field}}$

$\approx 1.$ It is not thought necessary to reproduce this item exactly since the field time is somewhat nebulous to begin with, and also because of the instrumentation and controls required. Instead of exact reproduction we shall therefore choose a convenient time increment approximately equal to that used in the field.

h. Lr = layer ratio - this item is left to empirical analysis.

i. Vr = volume ratio - left to empirical analysis.

j. Ar = contact area ratio - left to empirical analysis.

k. Er = compactive effort ratio $\approx$ 1.

We can now clearly define the limits of this research. It is recognized from the start that to derive all the empirical relationships apparently required is impossible in the time available for this study. We therefore confine this investigation to determining conditions under which Er $\approx$ 1. It is assumed that this condition is reached when the field curve of per cent moisture content (of dry weight) versus dry density is essentially reproduced with the laboratory apparatus. An attempt will also be made to postulate on the empirical relationships based on limited data (See Chapter VI). It is hoped that further research will be carried on by others to more definitely define the empirical relationships referred to above.

CHAPTER IV DESCRIPTION OF APPARATUS

A. General Description

A laboratory compactor (See Appendix B) was designed for this investigation in keeping with the guide specifications outlined at the end of Chapter III "Theoretical Considerations". The compactor incorporates some of the ideas used by Osterberg and Rutledge in their "Kneading Action Compaction Device" (Ref. #11), principles incorporated by Wilson in the "Harvard Miniature (Ref. #25), and some original ideas of the authors. As this section is studied, the reader should refer frequently to Appendix B in which a complete set of pictures and drawings may be found to facilitate understanding of the descriptive material presented below.

Compaction is accomplished by raising the compaction mold into the piston through a lever system with sufficient mechanical advantage to obtain the desired applied unit pressure. The compacting force is read on the extensometer dial which is actuated by the deflection of a standard proving ring.

The machine is built consistent with the specifications outlined in Chapter III and the limited time available for conceptual design. The platform is dimensioned to take molds from 2-1/2" to 6" in diameter. The piston head is removeable to facilitate investigation of various sizes and shapes of the compacting foot. A mechanical advantage of 10-1/2 to 1 is furnished so that a sufficient range of applied pressures can be attained. It is also easy to lengthen the lever arm should more mechanical advantage be required.

B. Detailed Description

In this section the compaction machine is described in detail, and reasons for certain features of the design are outlined. The machine is divided into the following assemblies (See Appendix B, Fig. B-1) to facilitate discussion:

1. Frame assembly
2. Proving Ring assembly
3. Piston assembly
4. Turntable assembly
5. Lever assembly

1. Frame Assembly (Fig. B-1 and B-2)

The frame consists of 4-5/8" steel rods threaded on both ends, and attached with standard nuts to standard 6" channel sections. The top channel is 15" long and the bottom 19-1/4" long. The choice of materials and dimensions is governed by clearances and materials which were available for use. These materials do not necessarily represent the best choice from a structural standpoint, but they are satisfactory. The purpose of the frame is simply to provide a mounting for the working parts of the compactor. The top channel has several sets of holes to facilitate changing the position of the proving ring for different size molds. This is necessary because the piston is off center relative to the center of the mold.

2. Proving Ring Assembly

The proving ring assembly is composed of the necessary mountings top and bottom, the proving ring itself, and a standard laboratory extensometer (Fig. B-2). Choice of rings depends on the range of pressures required for a given test. This in turn is dependent on total load and area of the compacting foot. Two rings were used in this investigation. For the lower pressures and smaller contact areas, a 400# capacity ring reading approximately 1.2#/div was chosen. For higher pressures and larger contact areas it was necessary to use a ring with 1000# capacity reading approximately 5.8#/div.

3. Piston Assembly

This assembly consists of the piston (7/8" steel rod), and the compacting foot (See Fig. B-1, detail A). The compacting foot is removeable, and several sizes and shapes were used during the course of laboratory tests (Figs. B-11 and 12). These are described at some length in Chapter V. Generally the foot is slightly rounded on the bottom (approximately on a 6" radius), and the piston is pivoted 1-1/4" above the top of the foot such that the foot is free to swing in a limited arc of 5°±. The rounding and pivoting are included so that irregularities in the soil surface will produce a slight rocking or kneading action similar to that obtained with a typical rubber-tired roller. This idea is much the same as the kneading arrangement incorporated by Osterberg and Rutledge in their machine (Ref. #11).

4. Turntable Assembly (Fig. B-2, detail B)

A 1-1/4" diameter steel rod supports a bearing and the turntable. The rod moves up and down guided by a 1-1/4" home-made bushing. The bushing is bolted to the bottom channel of the frame assembly. The turntable is attached to the bearing with a screw such that the table is free to rotate continuously in a 360° traverse, but cannot displace up or down. The turntable (5/8" steel plate, 7-3/8" diameter) is provided with mountings (Figs. B-3 and 10) for the various molds used in the test. The 1-1/4" rod has 3/8" holes spaced 1" center to center for pinning the rod to the end of the lever.

5. Lever Assembly

The lever assembly consists of the fulcrum, lever, and pin (Figs. B-1 and 10). The fulcrum is 4" center to center from the 1-1/4" rod of the turn-table assembly. The fulcrum is made from scrap material, and therefore it is only important to describe its key dimension and details of the topmost part. The fulcrum pivot point is 8-1/2" from the bottom channel of the frame. The top of the fulcrum is provided with a roller (3/8" hardened drill rod) so that the lever will slide easily when the lever arm changes as the end of the lever tries to move in a circular arc. The fulcrum roller is housed in a slot or guide so that the level cannot displace sideways (Fig. B-2, side elevation). The end of the lever is a machined piece, U - shaped to fit around the 1-1/4" rod which supports the turntable. A clearance of 1-1/4" is provided between the pin hole and the bottom of the "U" in order that the lever be able to swing freely for maximum lift. The lever itself is 1-3/4" x 1/4" steel stock, 47" long. The short arm is 4" when the lever is horizontal, and this arm lengthens as the lever moves up and down.

C. Operating Instructions

Description of the manner in which the machine operates is presented in the form of operating instructions. Instructions are amplified by pictures in Appendix B where applicable.

1. Choose variables for test depending on the investigation involved. It is necessary to compute an extensometer dial reading for the desired unit pressure (See Chapter VI., Sample Calculations). Choice of number of coverages, mold size, foot size and shape, time increment, and number of layers is also described in Chapter VI.

2. Mount the mold and collar on the turntable (Fig. B-3). This is done by tightening bolts on the rods provided for holding the mold in place. Note the use of wax paper to prevent leakage of pore water and to keep soil from sticking to the turntable when the compacted specimen and mold are removed from the machine.

3. Add sufficient soil for one layer (Fig. B-4). The number of spoonfuls of soil to be added for uniform layer thickness is easily estimated after a minimum of experiences with any given mold.

4. Pin lever to the 1-1/4" rod supporting the turn-table (Fig. B-5). Notice in the picture, the use of a block of wood to support the turn-table assembly during pinning. Choice of hole in the 1-1/4" rod is a matter of convenience. With a little experience, the operator soon learns which hole is the best choice for any given condition.

5. Depress the end of the lever thereby raising the sample into contact with the compacting foot (Fig. B-6). When the extensometer dial reaches the computed reading, hold this pressure for the previously specified time increment. Time may be controlled with a stop watch. It was found that an experienced operator could easily control time by simply counting aloud.

6. After the given time increment, release pressure by raising the level (Fig. B-7).

7. Rotate the turn-table to a new location (Fig. B-8). The operator chooses this new location based on the number of pressure applications required for one full coverage of the soil surface. He should arrange his successive locations so as to provide overlap. It has been found convenient to mark and number locations on the turntable so that the operator can easily keep track of the number of applications and coverages.

8. Repeat steps 5 thru 7 until the desired number of coverages for one layer has been accomplished. Remember that a coverage is defined as one application of the specified pressure over the surface of the mold.

9. Add soil for each succeeding layer and repeat steps 5 thru 8. As the thickness of sample increases, it will probably be necessary to repin the lever in a higher hole on the 1-1/4" rod.

10. After the given number of layers has been compacted, remove the mold.

11. From here on normal laboratory procedure for trimming, weighing, and extracting water content samples is followed (Ref. #8).

CHAPTER V TEST PROGRAM

This chapter is devoted to a description of the test program resorted to in evolving the conclusions and recommendations of this study. Presented herewith is a description of the soil, details of the various tests, analysis of sources of error, sample calculations, and partial analysis of results obtained. Partial analysis is made from the curves taken at face value in this chapter. Final analysis presented in Chapter VI is a re-evaluation of the partial analysis in light of the precision study and the amount of data obtained in these tests. Reference is frequently made to figures and charts in Appendices A, B, C, and D.

A. Soil Description - The soil used was obtained from a zone of weathered loess in the vicinity of Vicksburg, Mississippi. It is most generally described as a lean silty clay, and identification test results (See Appendix A, Fig. A-1) show that the soil is a representative sample of the same soil used in Reports 2 and 7 (Ref. No's 17 and 22) in which the field studies made at Vicksburg are described. The following is a visual description of the soil following the "Unified Soil Classification System" promulgated by the U. S. Army Corps of Engineers:

Dry Strength - Medium

Dilatancy - Slow to Medium

Toughness - Medium

Color - Light Tan

Organic Matter - Negligible, small amount of roots and dry weeds

Passing #200 sieve - 91%

Data From Liquid Limit, Plastic Limit, Specific Gravity, and Hydrometer

Analysis Tests - (See Appendix A, Fig. A-1)

CLASSIFICATION - CL

In addition to normal identification tests, the following was done as a matter of curiosity: It was postulated that if we did in fact have the same soil, it should be possible to reproduce a moisture density curve obtained by some standard test. Consequently a test was conducted by normal dynamic methods. This test was done with the same mold size, hammer weight, height of fall, etc., as a test run at Vicksburg. The Vicksburg curve and the MIT curve are shown on Fig. A-2. Also see Table A-2 for pertinent data. Note that height of sample at Vicksburg was 4.5" whereas height of sample in the comparitive MIT test was 5.0". This difference is due to limitations imposed by laboratory equipment.

Note also that the grain size analysis (See Fig. A-1) is not as close as it might be expected to be with the same soil. This is not considered significant since the Vicksburg analysis was by hydrometer only whereas the MIT analysis was of the combined type. It should also be recognized that some experience is required to run the hydrometer test properly; and the hydrometer analysis conducted for this study was made by inexperienced personnel.

With regard to soil identification, it is very important that the reader be reminded of a significant fact in the past history of this soil. The soil used at Vicksburg in their Report #2 (Ref. #17) was this silty clay taken from a virgin deposit. The soil in Vicksburg's Report #7 (Ref. #22), and the soil obtained for this study was not virgin soil. The latter was taken from previously used test sections, and was therefore subject to varying compactive efforts in the initial tests. The reader is referred to Report #7 (Ref. #22) for data on the effect of recompacting this soil by dynamic methods. No investigation has been made of the effects of recompacting by the kneading method treated herein.

B. Method of Preparing Soil

Normal laboratory procedure was followed in processing soil for the various tests. The soil was first air-dried at room temperature. All lumps were then broken down by sieving and by use of a rubber-covered pestle. That fraction retained on the number 6 sieve was then scalped out. This fraction amounted to less than 4% of the total sample by weight, and consisted of heavy rock particles which could introduce errors in unit weight in a 2-1/2" diameter mold. This problem is common in compaction tests, and has been under limited investigation for some time (Ref. #3). Thus far no theory or reliable system has evolved to compensate for this error. However, various arbitrary methods are used to take this discrepancy into account. A common device is to scalp out all material retained on a given sieve. For example, in the Standard AASHO Test, all material retained on the #4 sieve is discarded (Ref. #8). In the British Standard Test, that portion retained on a 3/4" sieve is scalped out (Ref. #3). The Corps of Engineers scalps out that fraction retained on a 3/4" sieve, and replaces this fraction with an equal weight of material passing 3/4" and retained on #4 in the Modified AASHO Test (Ref. #8). Using these examples as a guide, the #6 sieve was chosen for scalping as follows:

$$\text{Volume ratio} = \frac{\text{Volume (Std AASHO)}}{\text{Volume 2-1/2" mold)}} = \frac{\frac{1}{30}}{\frac{1}{117}} = 3.9$$

$$\text{Length ratio} = (\text{Volume ratio})^{1/3} = 3.9^{1/3} = 1.575$$

$$= \frac{\text{L (Std AASHO)}}{\text{L (2-1/2" mold)}} = \frac{\text{Screen size (Std AASHO)}}{\text{Screen size (2-1/2" mold)}}$$

Then, Screen size 2-1/2" mold $= \frac{.187}{1.575} = .119"$ opening. The closest standard sieve opening is .132".

Soil passing the #6 sieve was then divided into 6 parts. Each part was subsequently prepared at a different water content. Water contents ranged from 11% to 25% of dry weight. The water was added with a spray, and the soil and water were mixed vigorously to obtain maximum uniformity. To further insure uniform water contents, the six parts were placed in large jars and allowed to cure at room temperature for a minimum of 24 hours before compacting.

C. Preliminary Plan for Compaction Tests

Before any attempt was made to reproduce field curves, it was necessary to determine how the machine reacted under varying conditions. Prior to any formal testing, several trial runs were conducted. The data for these tests is not given in the report since the tests were repeated later on in the formal testing. Results of this preliminary testing showed that the machine yielded smooth uniform curves, that these curves could be easily reproduced, and that different operators could produce the same results using the same test procedure. With this evidence that the machine functioned in a reliable fashion, it was now possible to investigate the effects of changing the so-called basic variables: contact pressure, number of layers, coverages, time increment, mold size, and foot size. In order to facilitate this basic investigation, a reference or base test was formulated. The variables used in this test were designed for convenience in order that each individual test could be easily controlled and conducted in the least amount of time. Variables chosen were: (See next paragraph for field variables)

Contact Pressure = 65 psi

Number of Layers = 3

Coverages = 6

Time Increment = 2 sec

Mold Size = 2-1/2" diameter x 3" high

Foot Size = 1/3 sector of a circle 1/8" less in diameter than the mold diameter

With the base test as a reference, it was then a simple matter to change one variable at a time to determine the effect thereof. Results of these tests are tabulated in Appendix C, tables C-1 through C-6; moisture density curves are shown in Figs. C-1 through C-6 of Appendix C; and these results are analyzed in the discussion which follows. Note that the zero air voids and 90% saturation lines are plotted on each of the moisture density curves cited above (Figs. C-1 through C-6) to facilitate analysis. In addition, the field curves which the authors are endeavoring to reproduce is likewise plotted on each figure. This field curve (Ref. #17) is for a rubber tired roller exerting 65 psi contact pressure, 8 layers, 6 coverages, each layer 6" compacted thickness, and roller speed of 2 to 6 MPH. Discussion of the basic tests follows:

1. Varying Contact Pressure (all other variables held constant). Refer to Appendix C, Table C-1, and Fig. C-1.

Study of the moisture density curves plotted on Fig. C-1 that increasing contact pressure gives a higher maximum density at a lower optimum water content as expected (Ref. No's 3, 17 and 22). Saturation on the wet side of the curve remains constant at approximately 92% regardless of contact pressure variation. A large increase in maximum dry density (3 LB) is reflected between 65 psi and 90 psi. No significant change in optimum density is apparent between 90 psi and 150 psi. Increase from 65 to 90 psi reduces optimum water content by 1-1/2%; whereas increasing pressure from 90 to 150 psi reduces optimum water content by only 1/2%. It would appear from these limited data that in the range of 90 psi, an optimum compactive effort is reached beyond which no significant change in moisture density relationships can be effected by increasing pressure.

2. Varying Number of Layers (Table C-2, Fig. C-2)

Increasing the number of layers has a twofold effect. The thickness of each layer is reduced, and the effect of a given tamp is transmitted to layers previously compacted a greater number of times. Fig. C-2 shows that saturation on the wet side of the curve is independent of the number of layers. Increasing the number of layers (or conversely reducing the thickness of each layer) gives a higher maximum dry density at a lower optimum water content as expected (Ref. #3). Note that the movement of the peak up and to the left is approximately the same for an increase from 2 to 3 layers as for an increase from 3 to 8 layers. This shows that the variation in location of peak point with change in number of layers possibly is an exponential rather than a linear variation similar to that shown for changing contact pressure above.

3. Varying Number of Coverages (Table C-3, Fig. C-3)

Some difference is noted in saturation on the wet side of the curve with change in number of coverages. Between 6 coverages and 18 coverages, saturation appears to increase from about 92% to approximately 95%. Increasing the number of coverages moves the peak point up and to the left with a greater change shown between 6 and 12 coverages than between 12 and 18 coverages.

4. Varying Increment of Time During Which Full Specified Contact Pressure is Maintained (Table C-4, Fig. C-4)

A time increment of 1/2 second reduced saturation on the wet side to 90% or 2% lower than the saturation for 2 seconds and 5 seconds. These limited data would indicate that a peak value of approximately 2 seconds exists (for the conditions or variables of this test) beyond which decreasing time increment will increase air voids in the sample. Also note that the peak point once again moves to a higher optimum dry density at a lower optimum water content with increasing time increment as expected (Ref. #11).

5. Varying Mold Size (Table C-5, Fig. C-5)

Increasing mold size with all other variables held constant moves the peak point up and to the left. Saturation on the wet side is independent of mold size. Intuition and results of past studies (Ref. #3, 17, 22, and 14) would indicate movement of the peak point down and to the right with increase in mold size. Results of this particular test in which increasing mold size gave an opposite movement of the peak point helps us to appreciate the infinitely complex relationship of the many variables involved in compaction. In order to obtain 65 psi contact pressure with a 1/3 foot and 6" diam. mold, the total load on the foot was increased on the order of 6 times between the 2-1/2" diam. mold and the 6" diam. mold (562 lbs for the 6" diam. mold as opposed to 96 lbs for the 2-1/2" diam. mold). Study of the Westergaard or Boussinesq methods for determining magnitudes of pressure at various depths below a loaded area shows that the heavier total load transmits more pressure to the same depth even though contact pressure in the two cases is equal. From this it can be seen that a simple increase in volume will not reflect a decrease of compactive effort in the resulting curves unless other more effective variables are also changed. In this particular case (Fig. C-5) then, the movement of peak point was probably a result of increase in total load rather than increase in mold size. In effect the variation of volume was damped out by variation of total load.

6. Varying Foot Size (Table C-6, Fig. C-6)

First we shall examine the changes in moisture-density relationships incurred by changing from a 1/3 circle foot to a 2/3 circle foot. The changes thus incurred are minor and may not have any particular significance. It would appear that increase in contact area (all other variables held constant) increases saturation on the wet side by approximately 1%, and increases maximum dry density to a negligible degree. It should be pointed out here that in addition to changing contact area the kneading characteristic was also altered. With the 1/3 foot, rocking was in the direction of the long axis of the foot and parallel to a chord of the circle described by the walls of the mold.

The 2/3 circle foot rocked in the direction of the radius of the mold (Fig. B-13) (Rocking with the 1/3 foot is described as "circumferentially" whereas rocking with the 2/3 foot is "radially"); and with the full foot, there was no kneading action. Also contact pressure on the full foot was more uniform since the bottom was flat. Note now that the full foot yielded no change in saturation on the wet side, but resulted in a considerably lower maximum dry density at a higher water content. We might therefore consider that foot size was not the variable which brought about the change but rather the presence of kneading action or lack thereof and the degree of uniformity of contact pressure.

D. Density Studies Arising from Observations Made During Tests of "C" Above (Refer to Appendix D).

Two significant observations were made while conducting the tests referred to in paragraph C above. It was noted that water collected between the bottom of the sample and the turntable surface during the process of compaction, and that the very bottom of the sample was considerably wetter than the top of the sample as a consequence. This phenomenon was especially apparent on the wet side of optimum. It was also noticed that when the foot rocked or kneaded radially, it always kneaded in the same direction; and that this resulted in a depression on the top of the sample in the center. The 1/3 foot for the 6" mold kneaded radially and always toward the center resulting in a cone-shaped depression in the center of the sample. Note here in order to avoid confusion, the 1/3 foot for the 2-1/2" diam mold rocks circumferentially as indicated previously. The 1/3 foot, 6" diam mold which is under discussion here, rocks radially as indicated. The 2/3 foot for the 2-1/2" mold rocked radially and toward the outside of the sample resulting in a small hump in the center of the sample. The hump for the 2-1/2" mold and 2/3 foot was not nearly as evident as the depression in the 6" diameter sample compacted with a 1/3 circle foot. These observations raised some interesting questions, and gave rise to two special studies which are described below.

1. Variation of Density and/or Moisture Content with Depth (Tables D-1 through D-4)

Collection of water in the bottom of the sample might indicate a general movement (however small) of pore water from top to bottom during compaction. If this is indeed what happens, it should be reflected by a difference in water content and/or density between various levels in the sample. From this it was postulated that the difference between field and laboratory moisture density curves might be partially due to the depth from whihh the sample is taken.

In order to examine the above reasoning, a test (65 psi, 6 coverages, 3 layers, 5 seconds, 2-1/2" mold, and 2/3 foot) was run as follows: each of the six samples (different water contents) was compacted according to the prescribed variables. The entire sample (with mold) was weighed. The sample was then extruded (opposite to the direction of the compactive effort) about half-way, and the portion remaining in the mold was shaved flush. A water content sample was taken from the removed portion of the specimen, and the portion remaining in the mold was weighed. The distance between the bottom of the mold and the surface of soil remaining in the mold was then measured, and finally a water content sample was taken from that portion remaining in the mold. With this information, it was possible to compute density and water content for the entire sample, top of sample and bottom of sample. For method of calculation see "Sample Computations".

Results (Table D-1) of the first extrusion test indicated that the top of the sample was considerably denser than the bottom at all water contents including the wet side of the curve. Scatter of points was appreciably greater than the scatter obtained in normal tests.

The curious results of this first extrusion test led to the conclusion that the process of extrusion was at least partially responsible. The next test in this series was therefore run with extrusion in the opposite direction (same direction as the compactive effort). This test resulted in more scattered data shown in Table D-2. Curves could be interpolated between the points obtained, but conclusions are not warranted because of the scattered points.

Despite erratic results obtained thus far in studying variation of density with depth, it was still felt that this line of thought merited some further research. The authors now resorted to a split mold, 3" in total height (same as the standard 2-1/2" diam mold used in other tests) and divided into three 1" sections. The mold was made such that the sample could be weighed and trimmed three times. By calculating remainders, it was possible to obtain densities and water contents for top, middle, bottom, and for the entire sample (See "Sample Computations"). Study of Table D-3 shows a trend toward greater density and greater saturation on the wet side for the middle of the sample. There is no rational explanation for this. Furthermore the scatter of points when plotted indicates that considerable error (See discussion of "Sources of Error") was introduced in blowing volumes up on the order of 350 times. Since erratic results continued to be the order of the day, it was concluded that further study of variation of density with depth would require more time and more accurate and elaborate methods of volume determination. Since time was limited, this study was dropped at this point. Note that curves are not included in Appendix D for the 3 tests just discussed. They are omitted lest the reader jump to conclusions based on inaccurate data.

A fourth test was made with regard to vertical drainage in the sample. Uptil this time all tests had been conducted with drainage sealed off in the bottom of the mold by wax paper. Test four in this series was conducted with a soaked porous stone (3/8" thick) at the bottom of the mold. This was done to allow drainage at the bottom of the sample. For each sample the stone was soaked for 3 minutes and then dried by blotting with a paper towel. This peculiar procedure was necessary since only one stone was available for the test. Table D-4 shows a lower maximum dry density at a higher water content for the test without porous stone. Drainage however, is not necessarily the cause for this effect. Thickness of sample was reduced from 3" to 2-5/8" by introducing the stone. Reference to Fig. C-2 reveals that the change which occured is a normal result of decreasing layer thickness. A curve is not included in the Appendix for this test since the data is inconclusive.

2. Variation of Density and/or Moisture Content Radially from the Center of the Sample (Tables D-5 and 6, Figs. D-5 and 6)

These two tests were conducted to investigate the significance of the depressions and humps referred to above. It was suspected that the sample had a greater density in the direction of rocking. It was also theorized that confining effects might well produce a greater saturation in the center of the sample on the wet side of optimum. Densities in the center of the sample were determined by excavating a hole in the center, weighing the soil extracted therefrom, and then measuring the amount of 30 weight motor oil required to fill the hole (See "Sample Computations").

For the 6" mold (Table D-5 and Fig. D-5), it was found that the center of the sample was indeed more dense than the outer annulus. It was also noted that saturation on the wet side is greater in the center of the sample.

In the second test with 2-1/2" mold and 2/3 foot (Table D-6 and Fig. D-6), density was greater in the outer annulus, and saturation was greater wet of optimum for the center of the sample.

Results of these two tests would indicate that density is indeed greater in the direction of rocking, and that confining effects in the center of the sample do produce greater saturation wet of optimum. The limited amount of data gathered, and the rough procedure used for determining volume of the center of the sample should caution the reader to accept these conclusions with a jaundiced eye. Further work along these lines might be warranted, but was not undertaken by the authors for lack of time.

E. SAMPLE COMPUTATIONS (Ref. #8)

1. Calculations for a typical complete test.

a. Variables

Contact pressure = 65 psi

Coverages = 6

Number of layers = 3

Time = 2 sec

Mold size = 2-1/2" diam. x 3" high $= \frac{1}{117}$ cu. ft.

Foot Size = Contact area = 2/3 sector of 2-3/8" diam. circle = 2.95 sq. in.

b. Extensometer dial reading

Force = 65 x 2.95 = 191.75 lb.

Calibration of proving ring on platform scale gives a dial reading of 162 for a net load of 192 lbs.

c. Number of tamps per layer

$$= \frac{\text{coverages x area of full circle foot}}{\text{actual foot size}}$$

$$= 6 \times \frac{3}{2} = 9 \text{ tamps}$$

d. Dry Density (γ_d)

Wet density $= \gamma_{wet} = \frac{\text{wet weight}}{\text{Volume of sample}}$

$$\gamma_d = \frac{\gamma_w}{1 + w}$$

e. Water content

$$= \frac{\text{Wet weight - Dry weight}}{\text{Dry weight}} = \frac{W_w}{W_s}$$

2. Determination of Density Top and Bottom of Sample by Extrusion

Method given: Weight of entire sample = 0.945 lb

Sample extruded opposite to direction of compactive effort.

Depth from mold flange to surface of sample after partial extrusion and trimming $= \frac{47}{32}$ "

Weight of soil remaining after extrusion = 0.461 lb.

Water content (top) = 12.6%

Water content (bottom) = 13.1%

Mold Volume $= \frac{1}{117}$ cu. ft.

$$\gamma_d \text{ (entire sample)} = \frac{117 \times 0.945}{1 + \frac{.126 + .131}{2}} = 98 \text{ pcf}$$

$$\gamma_d \text{ (bottom)} = \frac{0.461 \times 117 \times 3 \times 32}{49\ (1 + .131)} = 93.5 \text{ pcf}$$

$$\gamma_d \text{ (top)} = \frac{(0.945 - 0.461) \times 117 \times 3 \times 32}{47\ (1 + .126)} = 102.6 \text{ pcf}$$

3. Determination of Density Top, Bottom, and Middle by Split

Method given: Weight of entire sample = 0.961 lb.

Weight of bottom = 0.327 lb.

Weight of middle and bottom = 0.658 lb.

Depth of mold = 3"

Depth of each section = 1"

Water content top = 13.4%

Water content middle = 14.2%

Water content bottom = 13.5%

Mold volume = 1/117 cu. ft.

$$\gamma_d \text{ (entire sample)} = \frac{0.961 \times 117}{1 + \frac{.134 + .142 + .135}{3}} = 99 \text{ pcf}$$

$$\gamma_d \text{ (top)} = \frac{(0.961 - 0.658) \times 117 \times 3}{1 + .134} = 93.8 \text{ pcf}$$

$$\gamma_d \text{ (bottom)} = \frac{0.327 \times 117 \times 3}{1 + .135} = 101.2 \text{ pcf}$$

$$\gamma_d \text{ (middle)} = \frac{(0.658 - 0.327) \times 117 \times 3}{1 + .142} = 101.7 \text{ pcf}$$

4. Determination of Density of Center of Sample by Oil

Displacement given: G of the oil = 0.891

Weight of soil excavated from center of sample = 97 gms

Weight of oil required to fill the hole = 48 gms.

$$\gamma\ \text{wet} = \frac{W_s}{W_o} \times G\ \text{oil} \times \gamma_w$$

$$= \frac{97}{48} \times .891 \times 62.4 = 112.5\ \text{pcf}$$

F. Study of Precision and Reliability of Results.

1. Compaction Machine

Due to the inherent simplicity of the machine, controls such as those incorporated in the Northwestern Kneading Compactor (Ref. #11) are lacking. Magnitudes of error which might conceivably be introduced are outlined below, and are analyzed with regard to possible effects on a typical moisture density curve. The errors are discussed with regard to a single point. It should be remembered in reading this presentation that many of these errors are likely to occur in the positive as well as the negative direction with equal frequency. Since moisture density curves at best represent an average of many points, errors which appear to be of significant magnitude are dampened out to the point of being negligible when the final curve is drawn. This fact becomes evident when the reader compares the relatively smooth curves usually obtained with the possible sources of error.

a. Contact pressure - The only means of controlling contact pressure is manual. The operator must keep the extensometer dial at the specified reading for the given time increment by exerting a constant force on the end of the lever. The maximum probable error is 3 divisions on the dial or 3 x 1.2 = 3.6 psi with the 400 pound capacity proving ring. Reference to Fig. C-1 shows that an error of 3.6 psi has negligible effects on any point above 90 psi, and can raise or lower the point on the order of 0.3 lb/cu. ft. at the lower pressures.

b. Layers - Two possible errors present themselves here. First, is the possibility of the operator miscounting the specified number of layers. This is unlikely to happen if reasonable care is exercised. If it did occur the resulting error in dry density would be on the order of 2 lb/cu.ft. at low number of layers and 1 lb/cu.ft. at higher numbers of layers (Fig. C-2). Since these errors would not occur at each point, the point in error would show up as a bad point when plotted, and would consequently be neglected. A second possibility is the likelihood of non-uniformity in layer thickness. This can be reasonably well controlled by carefully measuring the soil required for each layer in the loose condition. The operator soon learns how many spoonfuls of soil are required to fill the mold under varying conditions. Since layer thickness is an average of the total sample height divided by the number of layers, any small deviations from uniform thickness are effectively dampened out.

c. Coverages - The number of coverages is also subject to the human error of miscounting. Once again this error is easily eliminated with reasonable care. However, should the error occur, study of Fig. C-3 reveals that an error of one coverage for one or two points on the curve is negligible (order of 0.2 lb/cu.ft. at more critical portion of the curve).

d. Time - Time is controlled by a stop watch or by counting. Errors in time increment of the order of 1/2 second are entirely possible. Maximum deviation of a single point due to a consistent error of

1/2 second is on the order of less than 1/2 lb/cu.ft. Also to be taken into account when viewing this possible error is the fact that time in the field is a random proposition at best. The reader is referred to Chapter III for a discussion of determining time rate of application of pressure in the field. See also "Sample Calculations" in this chapter.

e. Mold Size - The error introduced by mold size is intimately related with the accuracy of scales used and the care exercised in trimming samples. Generally the smaller the mold, the larger the likelihood of error since errors are magnified by a larger factor in blowing mold volume up to units of pounds per cu. ft. The maximum probable error in sample weight is estimated to be 0.01 lb. For the 2-1/2" mold, 3" high (V = 1/117 cu. ft.), error is 1.2 #/ ft^3 in wet density. For the 6" mold, 3" high (V = 1/20.3 cu.ft.), error is 0.2 #/ ft^3 in wet density. These errors are further reduced when converted to dry density depending on the magnitude of water content.

f. Summary - If all of these errors were to occur consistently and in the same direction for each point on a curve, the peak point would be displaced on the order of 4 to 5 lb/cu.ft. with a like deviation in optimum water content. Errors of the same order of magnitude are equally possible with present standardized tests. When considering this error, the reader should keep in mind that with due care in experimental procedure, the possibility of significant error is easily eliminated. Controls to eliminate the large majority of possible errors in a positive fashion can be incorporated in the machine. The added expense however, is not considered warranted in light of the preceding discussion.

2. Errors in Laboratory Procedure

a. Normal procedure

(1) Dry Density (See 1 e above)

(2) Water Content - An error of 1 gm in dry weight for a sample weighing 100 gms wet yields an error of 1% in water content. The scales are accurate to 0.1 gms; hence this error assumes negligible proportions.

b. Determination of Density Top and Bottom by Extrusion

Errors can be introduced in weighing, and by virtue of change in length of sample induced by the extrusion process. In this method and in the method analyzed in c below, weighing errors are more serious than usual since more weights are determined for the same sample or parts thereof. When determinations are made by use of residuals as in the extrusion or split mold method, errors in weighing become cumulative. For errors of .01 lbs, 1/64" in length measurement, and 1/32" shrinkage of sample after extrusion, the order of magnitude of error in dry density is 4 pcf.

c. Determination of Density Top, Bottom, and Middle by Split Mold (See discussion in b above relative to cumulative weighing errors).

An error of 0.01 lbs in weighing results in a difference in the order of 3 pcf in dry density.

d. Determination of Density of the Center by Oil Displacement

Because of low permeability of the sample and viscosity of the oil used, losses of oil due to seepage may be neglected. It is extremely difficult in this method to insure that the oil surface is indeed in the same plane as the soil surface around the perimeter of the excavation. Practice reduces this error somewhat, but it cannot be eliminated entirely. This could easily result in a 2 gram error in weight which would bring about an error on the order of 5 pcf in dry density.

CHAPTER VI RESULTS AND CONCLUSIONS

In Chapter V of this report a limited amount of analysis was presented for each of the tests conducted during the course of the investigation. This chapter is devoted to an appraisal of the data analysis in Chapter V in light of the discussion of accuracy also presented in Chapter V. As these results are evaluated in this chapter, certain conclusions will be drawn. The conclusions thus drawn will be summarized at the end of the chapter.

In studying the conclusions drawn from this investigation the reader must keep the limitations of the study constantly in mind. It therefore becomes necessary to preface the presentation of Chapter VI with a few general remarks. These data are for one soil only, and the number of tests conducted is limited at best. All conclusions must consequently be accepted in the light of these two primary limiting factors. The data gathered can be used to demonstrate the qualifications of the MIT Compactor as a new piece of laboratory equipment. Otherwise the data indicate but certainly do not prove any hypothesis presented in Chapter III. These indications in most cases however, are considered sufficiently encouraging to be worthy of further research along these same lines. It is believed that such research will substantiate the indications of data available herein. The major contribution of this work is therefore conceived to be a new laboratory compaction apparatus, techniques developed for its use, and the established accuracy of data obtained through its use. Another significant, if somewhat secondary, contribution is the initial rough developement of a fresh approach to the general problem of reproducing field compaction in the laboratory.

A. Conclusions Relative to the "MIT Compactor" (or "CW Compactor")

For normal testing, possible errors resulting from lack of controls and the ever-present human equation are considered negligible (See Precision Study, Chapter V). The following basic conclusions with regard to the machine are therefore warranted:

1. An increase in contact pressure, number of layers, number of coverages, and time increment increase the compactive effort. This is shown in Figs. C-1 through C-4 where an increase in any one of these variables results in a higher maximum dry density at a lower optimum water content. This direction of peak point movement is generally accepted as an indication of increased compactive effort (Ref. #15).

2. Kneading or rocking action gives a different result than pure static compaction. This is clearly demonstrated in Fig. C-6 in which the 1/3 and 2/3 circle feet were used in conjunction with kneading action whereas the full circle foot was used without kneading.

3. The machine is easy to use, well-adapted to changing a multitude of variables for research, accurate, not subject to overt experimental or human error, and extremely rugged. The reader should review "Operating Instructions" in Chapter IV, Figs. B-1 and B-2, pictures in Appendix B, and the uniformity of experimental points in Figs. C-1 through C-10 to satisfy himself that these conclusions are valid.

B. Indications Based on Limited Data

Although not within the specific scope of the study, the following indications presented themselves in conjunction with certain of the tests conducted. These are merely observations based on a minimum of data, and are given here to complete the analysis, and to raise questions for further research and study.

1. It is possible that increasing contact area results in

greater saturation wet of optimum (See Fig. C-6).

2. It is possible that the sample is more dense in the direction of rocking or kneading (See Figs. D-5 and 6, also discussion of "Oil Displacement Method", Chapter V).

3. It is possible that confining effects yield a greater density in the center of the sample (Compare Figs. D-5 and 6, and refer to discussion of "Oil Displacement Method", Chapter V).

4. It is possible that limited drainage within the sample during compaction results in a variation in density and/or water content with depth (See discussion Chapter V).

The reader is reminded here that the accuracy of extrusion, split mold, and oil displacement tests is of such a low degree that the results of these tests are relatively inconclusive.

C. Analysis of "Best Tests"

Up to this point no mention has been made of the tests which in truth satisfy the expressed intent of this investigation, ie., "To simulate field density curves". This was done by design rather than ommission in order that the basic variables might be well-digested before examining the results of these tests. The term "Best Test" as used in Figs. (C-7, C-8, C-9, & C-10) requires definition. "Best" is used in the sense of that curve which most closely approximates a given field curve. "Best" does not connote the best data for several tests under the same conditions as might well be implied by the bare term "Best Test". It should be remembered that the field curve is the mean for a great many points of considerable scatter (See actual field points on Figs. C-8 and 9). The field curve then represents a band of values rather than a well defined curve such as is obtained in the laboratory. To reproduce this field curve per se is therefore not deemed significant. However, a laboratory curve which falls in the band of field points is considered significant. For ease of reference in discussing comparisons between field and laboratory results, the field curve will be used; but the reader should temper his thoughts with the concept of a band of scattered points for the field.

Comparison of field and laboratory curves is presented in terms of the following indices of analysis:

1. Maximum dry density
2. Optimum water content
3. Saturation wet of optimum
4. Visual inspection of shape of the curve
5. Reduction in dry density at ± 2% of optimum water content. This is a convenient arbitrary evaluation of the shape of the curve.

These five indices are presented in tabular form below (Table VI-1).

TABLE VI-1

Comparison of Field Curves vs "Best" Laboratory Tests

	Curve Identification	Reference	Max. γ_d pcf	opt ω % W_s	Visual Analysis of Shape	$\Delta\gamma_d$	From opt. ω	Sat. Wet of opt [redacted]
						+ 2% pcf	- 2% pcf	
Field	Contact Pressure = 65 psi 8 Layers (6" compacted thickness) 6 Coverages Time ≈ 1/2 sec (2 to 6 mph)	Fig. C-7 &	109.0	19.3%	Same General Shape	2.5	2.5	97%
Lab	Contact Pressure = 65 psi 5 Layers (3/8" compacted thickness) 6 Coverages 2 Sec 2 1/2" Diameter mold, 2/3 foot	Table C-7	109.5	17.9%		2.5	2.5	93%
Field	50 Psi 5 Layers (6" ea.) 4 Coverages Time ≈ 1/2 sec (3 to 5 mph)	Fig. C-8 &	107.2	19.3%	Same General Shape	2.4	1.7	95%
Lab	50 Psi 8 Layers (3/8" ea.) 4 Coverages 1 Sec 2 1/2" Diameter mold, 2/3 foot	Table C-8	106.3	18.3%		1.8	1.6	93%
Field	90 Psi 5 Layers (6" ea.) 4 Coverages Time ≈ 1/2 sec (3 to 5 mph)	Fig. C-9 &	111.0	17.5%	Slopes Steeper on Field Curve	3.8	3.5	91%
Lab	90 Psi 8 Layers (3/8" ea.) 4 Coverages 1 Sec 2 1/2" Diameter mold, 2/3 foot	Table C-9	110.0	16.5%		3.5	1.8	92%

Study of Figs. C-7, 8, and 9 and the material presented immediately above in chart form show that the so-called "best" tests do essentially reproduce their field counterparts. They are certainly within the aforementioned band of scattered field points. This alone has no particular significant value other than substantiating what Wilson and Osterberg (Ref. #25 and 11) have already demonstrated with their compaction machines. The significant importance of these "best" tests is that they were conducted with the same or similar variables as the field tests in conformance with the theoretical considerations in Chapter III. Note that in each case of laboratory curve vs field curve, the contact pressure and coverages is the same, time is approximately the same, and only layer thickness is appreciably different between field and laboratory variables.

Fig. C-10 shows the field curve, closest MIT curve, and the closest curves from available literature (See Appendix C, Comparison of Tests under Table C-9) obtained with the Harvard Miniature Compactor and the Northwestern Kneading Compactor. Note the similarity among these curves and their relative position to one another. The following (Table VI-2) is a tabulation of the indices of comparison for all 4 curves. All four curves lie within the band of scattered field points showing that the laboratory method of kneading compaction may well approximate field compaction with a rubber tired roller. In order to make a fair comparison, the reader should realize that the Harvard and Northwestern curves probably do not represent an effort to reproduce the field curve shown. These curves are from available literature, as mentioned above, and were chosen because they are the closest published curves (closest to the specific field curve shown on Fig. C-10). Also the reader's attention is invited to Fig. A-2 where he will see clearly that the Standard AASHO

TABLE VI-2

Comparison of Field Curve vs MIT, Harvard, and Northwestern Curves (See Fig. C-10)
* Denotes closest to field curve - where 2 stars are shown, equal proximity is indicated.

	Curve Identification	opt γ_d pcf	opt w % W_s	Visual Analysis of Shape	$\Delta \gamma_d$ From opt: opt w + 2% pcf	$\Delta \gamma_d$ From opt: opt w - 2% pcf	Sat. Wet of opt
Field	Contact Pressure = 65 psi 8 Layers (6" compacted thickness) 6 Coverages Time ≈ 1/2 sec (2 to 6 mph)	109.0	19.3	-	2.5	2.5	97%
MIT	#Contact Pressure = 65 psi 8 Layers (3/8" compacted thickness) # 6 Coverages 2 sec 2 1/2" Diameter mold 2/3 Circle foot (240° sector)	* 109.5	17.9	* Same as Field	* 2.5	* 2.5	* 93%
Harvard	Contact Pressure = 200 psi 10 Layers (0.3" compacted thickness) 3.7 Coverages Time - Not measured (1/2 sec) 1 5/16" Diameter mold 1/2" Diameter circular foot	* 108.4	* 18.3	Shallower Slope on Dry Side	1.6	3.2	90%
Northwestern	Contact Pressure = 200 psi 5 Layers (0.9" compacted thickness) 4 Coverages Time = 2.4 to 3.0 sec 6" Diameter mold 360^0 sector foot	110.6	16.6	Same as * Field	2.8	2.1	90%

\# Denotes same as field

curve is not within the specified band of scattered field points.

With the above information in mind we can now refer back to Chapter III "Theoretical Considerations" to re-evaluate and amplify the theory presented. Compactive effort has long been described in terms of foot pounds per unit volume. This method of expressing so-called compactive effort is deemed a misrepresentation. The term compactive effort should involve a combination of variables which produce the same effect on the soil mass compacted when a function of these variables yields the same result. The fact that foot pounds per unit volume is a misrepresentation is then easily pointed out by compacting 2 samples by normal dynamic methods such that the product of 2 different sets of variables (No. of blows, hammer weight, height of fall of hammer, etc.) gives the same foot pounds per unit volume. The 2 moisture density points will not be the same. We must therefore seek a better means of expressing compactive effort. The analysis below attempts to do just this:

Variables

E = Compactive Effort
P = Contact Pressure
C = Number of Coverages
N = Number of Layers
L = Thickness of one Compacted Layer
T = Time Increment During Which Peak Contact Pressure is Maintained
V = Volume of Sample

Assumptions

Assume same soil is used in field and laboratory.

Assume method of compaction is essentially duplicated if the laboratory moisture density curve lies within the band of scattered field points.

Assume temperature and relative humidity considerations are negligible if the laboratory test is conducted at normal room temperature.

Assume velocity of impact is the same in the laboratory and the field if the laboratory moisture density curve lies within the band of scattered field points.

With the above assumptions, it can now be shown that

$$E = f\,(P, C, N, L, T, V).$$

It can further be shown from the partial analysis of basic data in Chapter V that E increases with some function of P, C, N and T; and further that E decreases with some function of "L" and "V". It has also been shown in this study that P and C can easily be made the same in field and laboratory. "T" cannot be made exactly the same since it is impossible to evaluate time in the field. However, Fig. C-4 indicates that the effects of varying time are of a low order of magnitude. Hence slight differences (order of 1/2 sec) between computed field time and laboratory time are not reflected in the moisture density curve. On this basis, this study would indicate that time in the field and time in the laboratory can be made the same for practical purposes. If the definition of compactive effort is accepted, then this study yields three different sets of conditions for which compactive effort is the same in field and laboratory (Figs. C-7, 8, and 9). The reader should now refer back to Chapter III "Theoretical Considerations". Here he will find a discussion pointing out that it is not feasible to reproduce field values of L and V in the laboratory. Since N is intimately associated with L for a given mold size, "N" also becomes difficult to reproduce. The reader may now recall that these particular items were reserved for empirical analysis in the theoretical treatment. The three sets of conditions referred to above (Figs. C-7, 8 and 9) are not considered to constitute sufficient data to attempt such an empirical analysis. However, it is possible to specifically evaluate both L and N in the laboratory and in the field. V is more difficult to determine, but it can be estimated reasonably well by the suitable application of pressure bulb theory. Since these three variables can be evaluated, it should be possible to isolate each one individually in the laboratory and thereby determine the pertinent functions.

From the results of this study and those of Osterberg and Wilson (Ref. #11 and 25), it is proposed that the approach outlined above be considered as a means of alleviating existing problems relative to compaction. These problems are enumerated in Chapter I. In order for this approach to become useful, the following supplementary test program would be required:

1. Tests similar to the ones used in this study but on different soils.

2. Strength tests to prove that like stress-strain characteristics are indeed obtained if the laboratory moisture-density curve lies in the zone of scattered field points.

3. Tests in which N, L, and V are isolated individually in order to evaluate their effects on E and thereby determine the unknown functions.

4. A series of check tests to prove the validity of proposed values of each function once these functions have been determined.

D. Summary of Conclusions

1. Compactive effort is increased by increasing any one or more of the following: contact pressure, coverages, time increment, and number of layers.

2. Compactive effort is decreased by increasing layer thickness or the volume of sample.

3. The kneading or rocking feature gives a different effect

than that obtained with pure static loading.

4. The C-W Compactor is a suitable apparatus for laboratory compaction meeting the general criteria of: simplicity, flexibility, ruggedness, adaptability, accuracy, and economy.

5. The general approach in this study involving laboratory and field variables and their relationship to compactive effort shows encouraging promise, and should be pursued further.

CHAPTER VII RECOMMENDATIONS

As in most studies of limited scope, this study seems to have raised more questions than it has answered. The value of this study is therefore extremely limited unless these questions are answered by further work along these lines. It is therefore considered necessary to summarize the more important questions raised by listing several recommendations. The authors respectfully recommend the following as a result of this brief work:

A. That the machine be investigated for general laboratory use other than compaction with a view toward obtaining a multiple purpose type of apparatus. For example the C-W Compactor can be easily adapted for an accurate cone penetration device. In cone penetration tests we usually apply a steady rate of strain and record deflections of a proving ring. Since the calibration factor of the ring is usually not constant, and steady strain is subject to human error, this procedure is not very accurate. With the C-W Compactor, the sample would first be compacted. Then the foot would be removed, and replaced with a cone. After this is done, place sufficient weight on the end of the lever to produce a given deflection on the proving ring. Now measure, with a stop watch, the time required to obtain the given proving ring deflection. This procedure is simpler to accomplish, and the results are more accurate.

B. Conduct tests on other soils (for which field data are available) to determine whether field moisture density curves can again be reproduced using the system suggested in this report.

C. Conduct strength tests on samples whose moisture-density coordinates lie in the band of scattered field points to determine whether these samples have the same stress-strain and strength characteristics possessed by field samples. These tests will prove or disprove the validity of certain assumptions made in developing the theory.

D. Conduct tests in which N, L and V are isolated and varied individually in order to evaluate their pertinent unknown relationships to compactive effort.

E. Conduct a final series of check tests using different combinations of variables to obtain Er = 1. If these tests continually show that Er in fact equals one, and that equal stress-strain and strength characteristics are obtained, then the theory can be accepted as valid. (Note $Er = \text{Compactive Effort Ratio} = \frac{\text{Laboratory Compactive Effort}}{\text{Field Compactive Effort}}$)

F. Recommendations for Improving the CW Compactor Should Another Unit Be Built.

1. Provide a clamp type or a threaded fitting on the end of the lever so that the lever can be easily lengthened should more mechanical advantage be required. This would increase the flexibility of the machine by allowing a wider range of total applied loads.

2. Provision should be made for a timing mechanism to eliminate this source of human error. This mechanism should be arranged such that the operator can actuate the timer from his position at the end of the lever when the specified proving ring dial reading is reached. After the desired time has elapsed a bell should ring at which instant the operator would release the pressure. The timer should be capable of accurate settings in 1/2 second increments between 0.5 seconds and 10 seconds.

3. A comfortable removeable handle should be furnished for the operator's end of the lever.

4. The fulcrum should be replaced with a solid piece of stock.

5. The lever should be furnished with a suitable means of attaching weights of known magnitude on the operator's end. This arrangement would serve a twofold purpose. The weights could be used as a means of controlling errors in contact pressure in precision testing. They could also be used as a surcharge to assist the operator in developing large total loads for high pressure testing.

6. The turntable diameter should be increased at least one inch in order to make testing with the 6" diam mold more convenient.

7. The turntable should have holes drilled in it and suitable fittings for attaching piezometers to these holes. This would provide the experimentor with a means of studying pore pressures during the process of compaction.

8. Lucite or plexiglass molds should be provided with the machine in order that the kneading action be more easily observed and studied.

APPENDIX - PART A

IDENTIFICATION TESTS

IDENTIFICATION TEST DATA

The following listed standard laboratory tests were run on the supply of Vicksburg Silty Clay in accordance with directions outlined in "Soil Testing for Engineers" by T. William Lambe:

Specific Gravity Test - Chapter II
Atterberg Limits Test - Chapter III
Grain Size Analysis - Chapter IV

Results of these tests run at M.I.T., and results of the same tests run at Vicksburg on the same soil are given in Figure A-1.

TABLE A-2

Standard AASHO Test *

Test Used

10 lb. Hammer
18 inch Drop

Sample Size

6 inch Diameter
5 inch Depth
5 Layers
12 Blows per layer
(Standard Effort = 12,000 ft. lb./cu. ft.)

Test Data

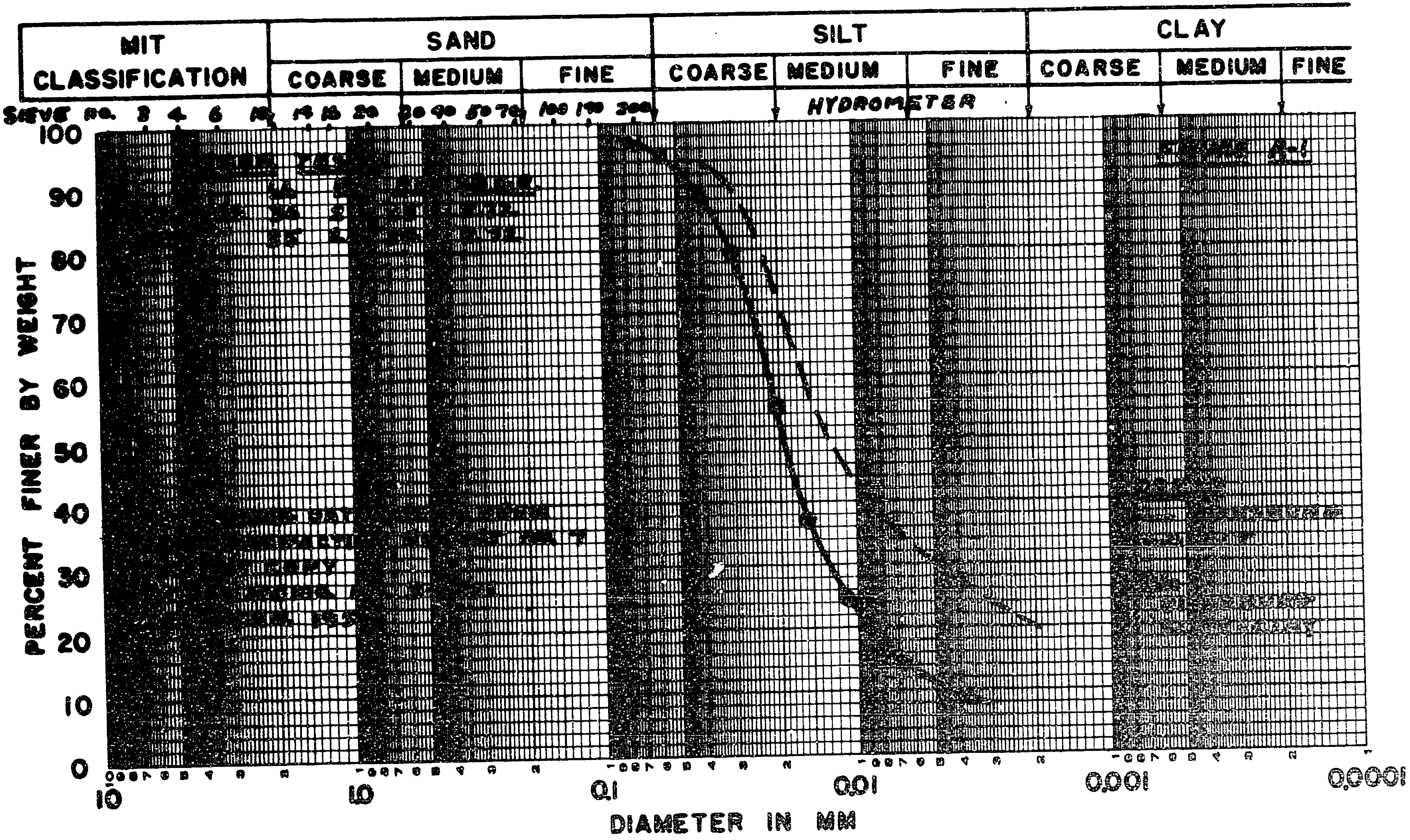
w	γ_d
9.8	99.2
13.2	103.3
16.5	106.7
19.2	105.2
23.0	98.8

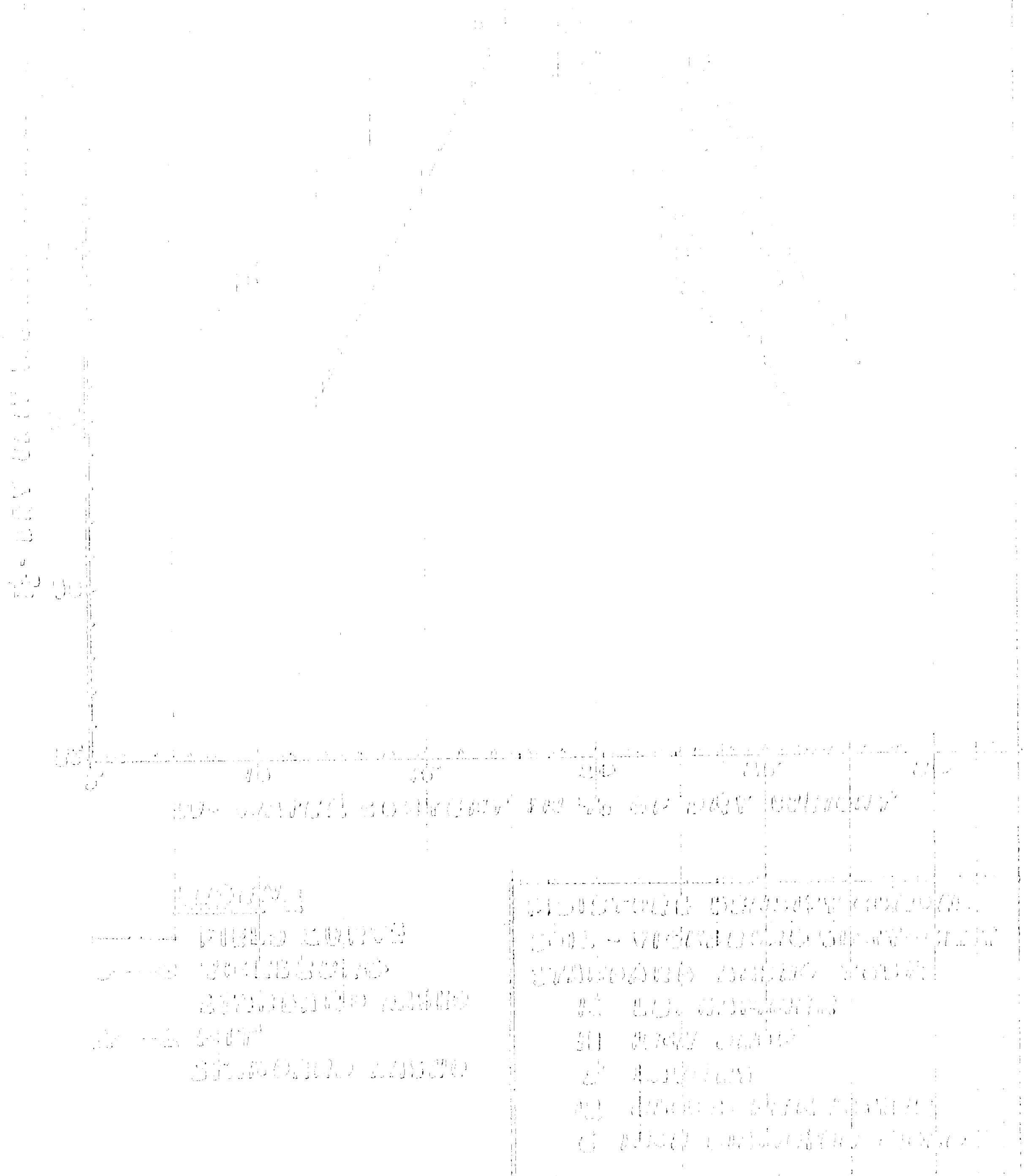
* Note - This test was conducted for the purpose of insuring that the soil used for this investigation was the same soil as that used in the Vicksburg field test. This is the same lab test (Standard AASHO Effort) as that made at Vicksburg, with the exception that the Vicksburg sample size was 6" diameter and 4.5" deep.

See Figure A-2 for comparison of curves obtained. Vicksburg Test data taken from Report No. 7 (Draft Copy), Plate 2, Tech. Memo, No. 3-271, Oct. 1955.

GRAIN SIZE DISTRIBUTION

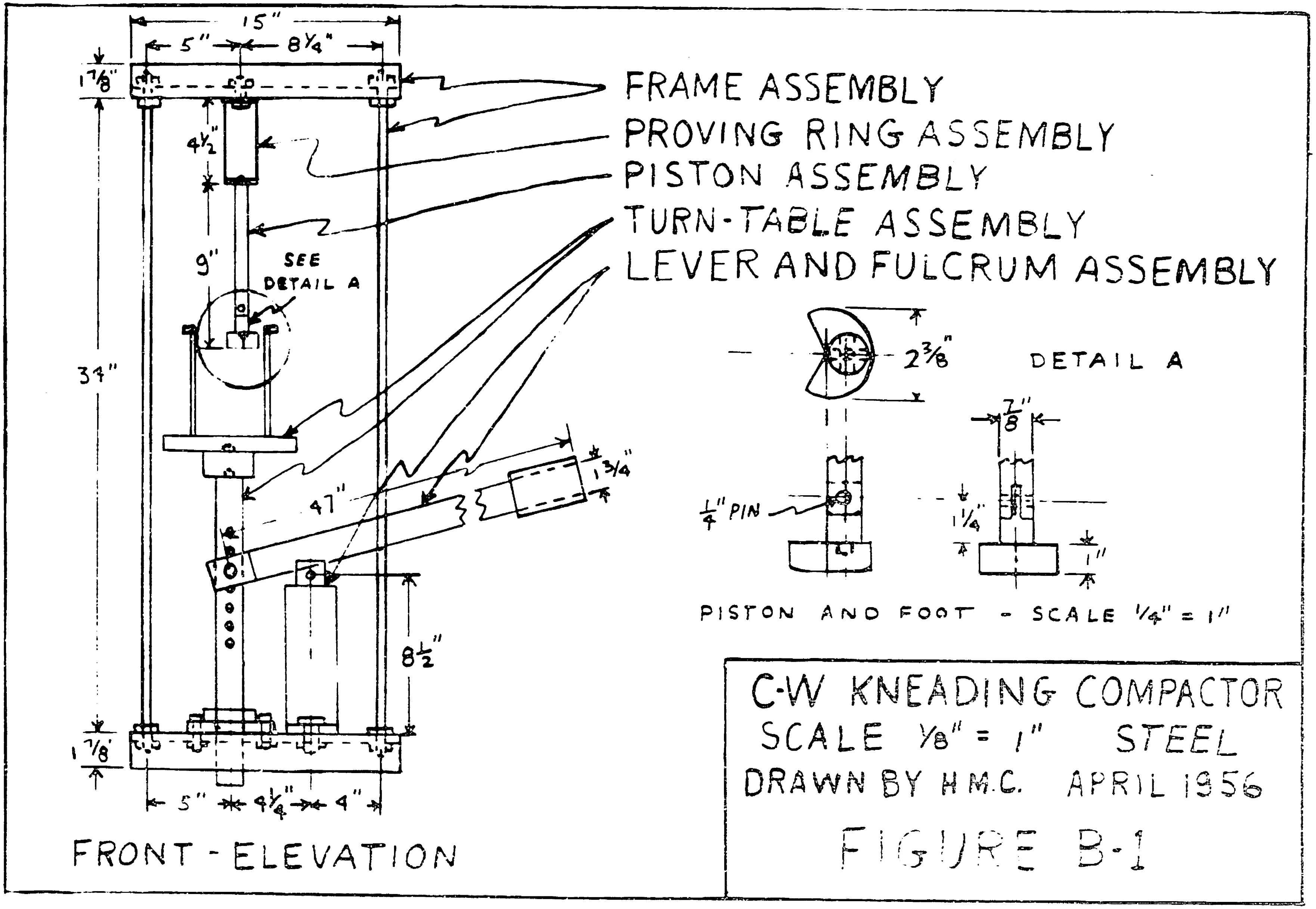
AND SOIL IDENTIFICATION TESTS




0
10
20
30
40
50

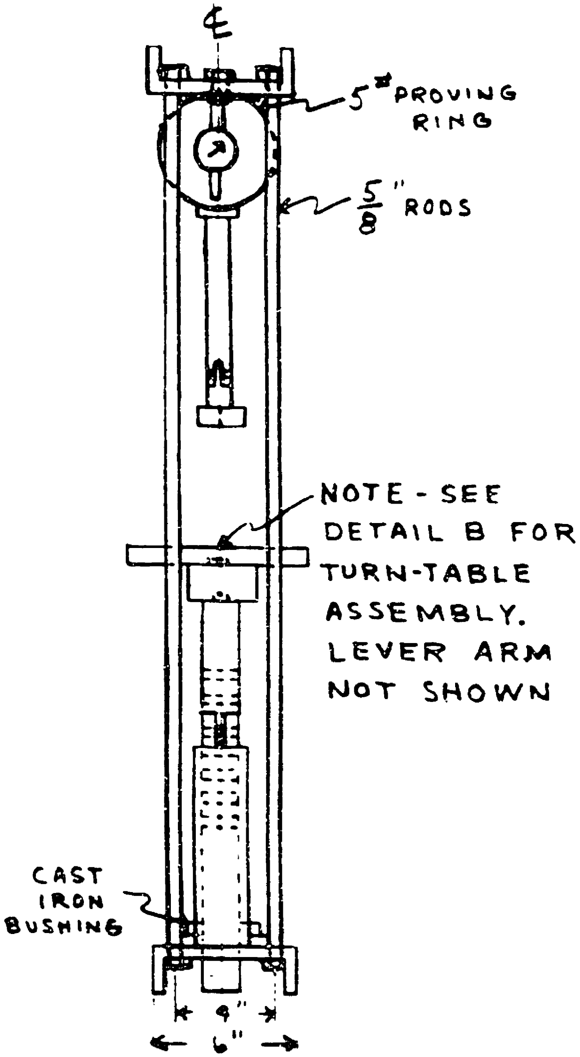
APPENDIX - PART B

SKETCHES AND PICTURES OF C-W COMPACTION MACHINE

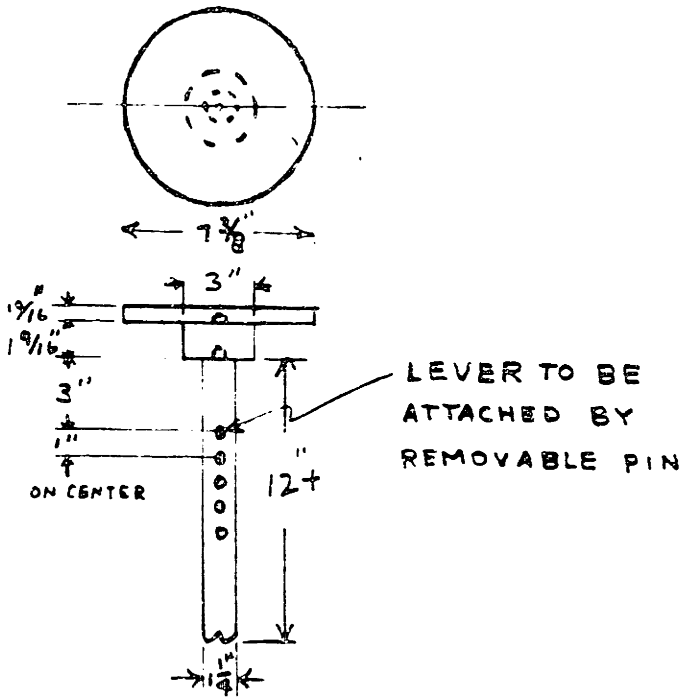


C-W KNEADING COMPACTOR
SCALE ⅛" = 1" STEEL
DRAWN BY H.M.C. APRIL 1956

FIGURE B-1



SIDE ELEVATION



DETAIL B - TURN-TABLE ASSEMBLY

C-W KNEADING COMPACTOR
SCALE 1/8" = 1" STEEL
DRAWN BY HMC. APRIL 1956

FIGURE B-2

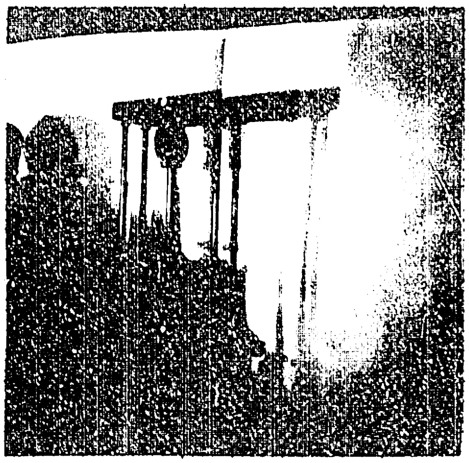


FIGURE B-3
MOUNTING THE MOLD

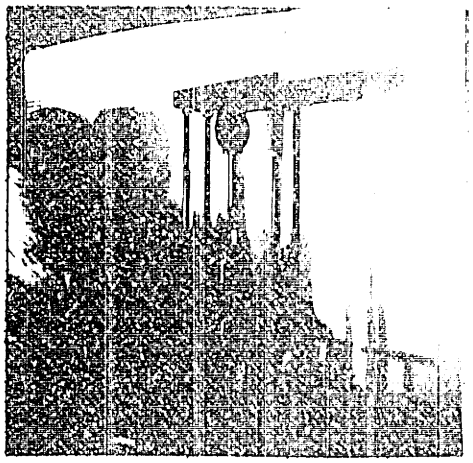


FIGURE B-4
ADDING SOIL

FIGURE B-5
PINNING THE LEVER

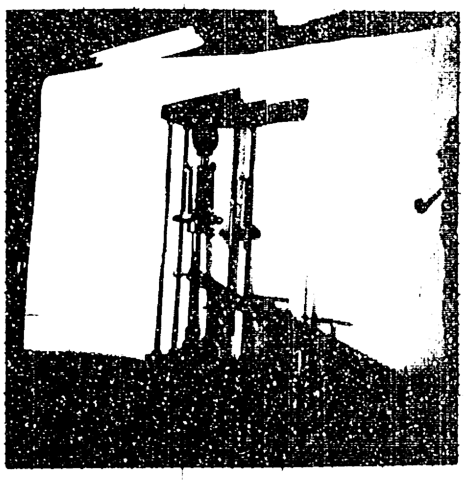


FIGURE B-6
APPLYING PRESSURE

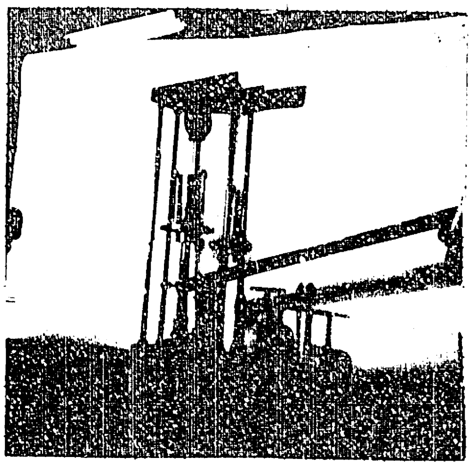


FIGURE B-7
RELEASING PRESSURE

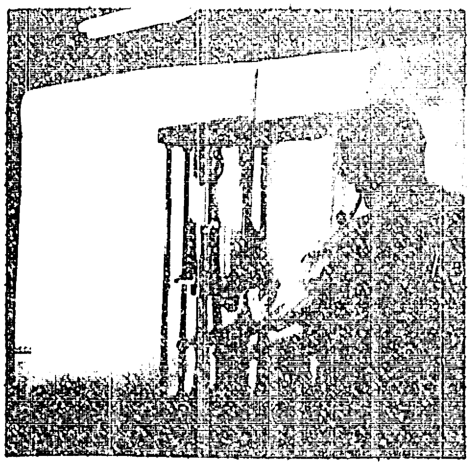


FIGURE B-8
ROTATING TURN-TABLE

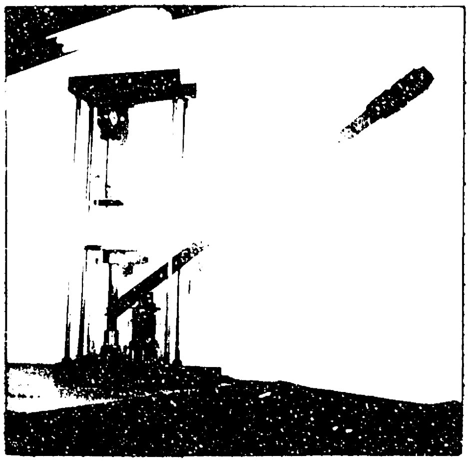


FIGURE B-9
MACHINE CONVERTED
FOR LARGE MOLD

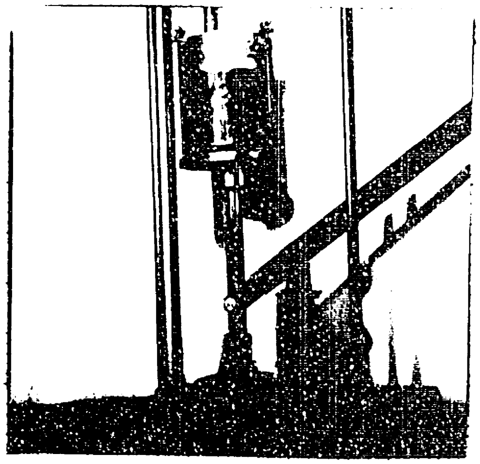


FIGURE B-10
LARGE MOLD
IN PLACE

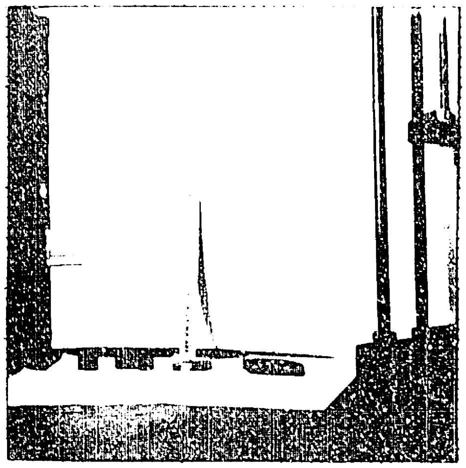


FIGURE B-11
TAMPING FEET
1/3, 2/3, FULL (SMALL MOLD)
1/3 (LARGE MOLD)
ELEVATION VIEW

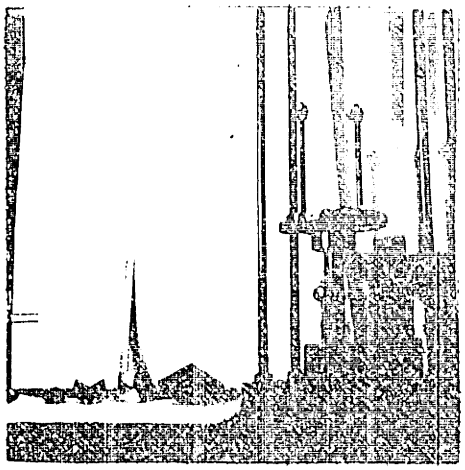


FIGURE B-12
TAMPING FEET
1/3, 2/3, FULL (SMALL MOLD)
1/3 (LARGE MOLD)
BOTTOM VIEW

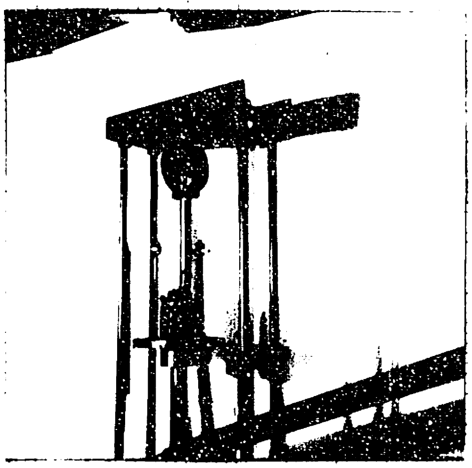


FIGURE B-13
SAMPLE UNDER PRESSURE
KNEADING ACTION SHOWN
MOLD COLLAR REMOVED

APPENDIX - PART C

TEST PROGRAM DATA

BASIC VARIABLES

AND BEST TEST RESULTS

MOISTURE - DENSITY CURVE TEST DATA

VARIABLE - CONTACT PRESSURE

TABLE C-1

TEST USED (Base Test)	TEST DATA Base Test		90 lbs. per sq. in.		150 lbs. per sq. in.	
	ω *	γ_d **	ω	γ_d	ω	γ_d
65 psi	11.7	97.5	11.9	102.7	12.7	105.7
3 layers	14.1	100.8	15.1	106.0	16.0	108.5
6 coverages	16.8	104.6	17.8	109.0	18.1	108.5
2 seconds	18.9	106.0	19.2	106.7	19.5	105.7
2 1/2 Diameter mold	21.9	103.1	20.6	105.0	21.8	103.2
1/3 Circle foot tamper	22.7	101.7	22.8	101.4	23.2	100.0

* - Note - (ω) Water content in % of dry weight

** - Note - (γ_d) Dry unit weight in pounds per cubic foot

VARIABLE - NUMBER OF LAYERS***

TABLE C-2

TEST USED (Base Test)	TEST DATA Base Test		Two Layers		Eight Layers	
	ω	γ_d	ω	γ_d	ω	γ_d
65 psi	11.7	97.5	12.9	95.5	11.9	102.8
3 layers ****	14.1	100.8	15.9	99.0	14.5	106.5
6 coverages	16.8	104.6	18.7	101.0	16.9	109.0
2 seconds	18.9	106.0	20.2	102.5	19.1	106.0
2 1/2" Diameter mold	21.9	103.1	22.9	100.2	20.9	104.1
1/3 Circle foot tamper	22.7	101.7	23.9	98.7	22.6	101.5

*** Note - A test was conducted using one layer, but the density was non-uniform and it was impossible to obtain a curve with any real significance.

**** Note - The mold used in this test is 2 1/2 inches in diameter and 3 inches deep. Therefore, the compacted layer thickness for the base test is 1 inch per layer.

MOISTURE - DENSITY CURVE TEST DATA

VARIABLE - NUMBER OF COVERAGES *

TABLE C-3

	TEST DATA					
TEST USED (Base Test)	Base Test		12 Coverages		18 Coverages	
	w	γ_d	w	γ_d	w	γ_d
65 psi	11.7	97.5	11.9	98.6	12.0	100.2
3 layers	14.1	100.8	14.1	101.6	14.3	103.0
6 coverages	16.8	104.6	17.2	106.1	17.2	107.3
2 seconds	18.9	106.0	18.9	106.8	19.3	107.0
2 1/2" Diameter mold	21.9	103.1	20.8	103.8	21.3	104.3
1/3 Circle foot tamper	22.7	101.7	22.7	101.9	23.0	102.5

* Note - One coverage in these tests corresponds to three tamps with the 1/3 circle foot tamper.

VARIABLE - TIME RATE OF APPLICATION **

TABLE C-4

	TEST DATA					
TEST USED (Base Test)	Base Test		1/2 Second		5 Seconds	
	w	γ_d	w	γ_d	w	γ_d
65 psi	11.7	97.5	12.8	98.0	12.7	99.6
3 layers	14.1	100.8	15.7	101.6	15.2	103.0
6 coverages	16.8	104.6	18.7	104.8	18.5	107.0
2 seconds	18.9	106.0	20.1	104.7	19.8	105.0
2 1/2" Diameter mold	21.9	103.1	21.6	102.2	21.8	103.1
1/3 Circle foot tamper	22.7	101.7	23.2	100.0	23.5	99.8

** Note - Time rate of application means the actual time during which the contact pressure was held constant per tamp. One point was tested at 10 seconds with the following result:

$$w = 21.8\% \qquad \gamma_d = 103.4 \ \#/\ ft^3$$

Since this density is almost exactly the same as the 5 second density for the corresponding water content, no further tests were made for increased times.

MOISTURE - DENSITY CURVE TEST DATA

VARIABLE - MOLD SIZE

TABLE C-5

TEST DATA

TEST USED (Base Test)	2 1/2" Mold		6" Mold (1st Run)		6" Mold (2nd Run)	
	w	γ_d	w	γ_d	w	γ_d
65 psi	11.7	97.5	13.4	97.8	11.5	98.5
3 layers*	14.1	100.8	14.6	103.5	13.9	102.1
6 coverages	16.8	104.6	16.9	107.0	16.5	104.9
2 seconds	18.9	106.0	18.1	107.8	18.3	107.5
2 1/2 & 6" Diameter Mold	21.9	103.1	20.1	105.7	21.4	102.5
1/3 Circle Foot Tamper	22.7	101.7	21.6	102.5	23.3	100.7

* Note - The tests on both mold sizes were run exactly the same way including a compacted layer thickness of one inch per layer.

VARIABLE - FOOT SIZE (Tamper) **

TABLE C-6

TEST DATA

TEST USED (Base Test)	1/3 Circle Foot		2/3 Circle Foot		Full Circle Foot	
	w	γ_d	w	γ_d	w	γ_d
65 psi	11.7	97.5	13.7	99.0	11.6	96.2
3 layers	14.1	100.8	16.0	102.6	15.1	97.9
6 coverages	16.8	104.6	18.7	106.2	17.1	100.5
2 seconds	18.9	106.0	20.3	105.2	18.7	102.0
2 1/2 Diameter Mold	21.9	103.1	22.7	102.5	21.0	103.2
1/3,2/3, & Full Circle Foot	22.7	101.7	24.2	99.3	25.1	97.6

** Note - These tests were run using the small (2 1/2" Diameter)mold and increasing the size of the tamping foot by 1/3 of a circle each time. For the 2/3 circle foot tamper 6 coverages were obtained by tamping nine times per layer.

MOISTURE - DENSITY CURVE TEST DATA

BEST TEST (Reduced Time) *

TABLE C-7

TEST USED (Base Test)	TEST DATA 2 seconds		 1 second	
	ω	γ_d	ω	γ_d
65 psi	13.0	102.5	11.9	98.4
8 layers	15.5	105.9	15.8	101.6
6 coverages	17.9	109.6	16.7	106.6
1 and 2 seconds	19.1	107.7	18.7	107.0
2 1/2" Diameter mold	21.3	104.5	21.2	104.0
2/3 Circle Foot Tamper	23.1	101.9	24.8	98.1

* Note - Both of these tests were run at 8 layers since it was determined that the this gave the closest results to the Field Curve. The 2 seconds test is considered the best test and the 1 second test was run to determine the effect of reducing the application time.

NEW FIELD CURVE (Four Basic Variables Changed) **

TABLE C-8

TEST USED (Base Test)	TEST DATA 5 Layers		 8 Layers	
	ω	γ_d	ω	γ_d
50 psi	11.9	97.0	11.9	97.5
5 and 8 layers	14.2	98.5	13.9	100.2
4 coverages	16.6	103.0	17.0	103.5
1 second	18.8	105.2	18.5	106.2
2 1/2" Diameter mold	20.9	104.9	20.8	104.0
2/3 Circle foot tamper	25.0	98.0	24.8	98.5

** Note - See special note for complete field data concerning field curves used in figures C-1 through C-8.

MOISTURE DENSITY CURVE TEST DATA

NEW FIELD CURVE (FOUR BASIC VARIABLES CHANGED)*

TABLE C-9

Test Used	Test Data	
(Best Test)	w	γ_d
90 psi	12.7	104.2
8 layers	15.1	106.8
4 coverages	17.5	109.5
1 second	18.5	108.0
2-1/2" dia. mold	20.9	104.6
2/3 circle foot tamper	24.3	99.2

* - Note - See special note for complete field data concerning field curve used in Fig.C-9.

COMPARISON OF TESTS

Fig. C-10 shows four curves including the original basic field curve used with original basic variables. The best curve (closest to field curve) obtained using the (C-W) MIT Kneading Compactor is the curve obtained using the data for the 2 second time interval from Table C-7. The other two curves shown on Fig. C-10 are:

(1) Harvard (Wilson Miniature) Curve for 200 psi and 3.7 coverages

(2) Northwestern (Osterberg Kneading Compactor) Curve for 200 psi and 2.4 seconds.

Data for these two curves were obtained from Fig. 3, opposite page 169, Proceedings Conference Soil Stabilization, MIT, 1952.

MOISTURE DENSITY CURVE TEST DATA

SPECIAL NOTE (FIELD DATA)

1. The following variables were used to produce the field curve shown in Figs. C-1 through C-7 and C-10:

Rubber Tired Roller

65 psi - average contact pressure

8 layers - compacted thickness 6 inches

6 coverages - 1 roller pass per coverage

1/2 - 1 second - Roller speed 2-6 mph.

Reference (17), Figure 17

2. The following variables were used to produce the field curve including points, shown in Fig. C-8:

Rubber Tired Roller

50 psi - contact pressure

5 layers - compacted thickness 6 inches

4 coverages - 1 roller pass per coverage

1/2 - 1 second - Roller speed 3-5 mph.

Reference (22), Plate 4

3. The following variables were used to produce the field curve including points, shown in Fig. C-9:

Rubber Tired Roller

90 psi - contact pressure

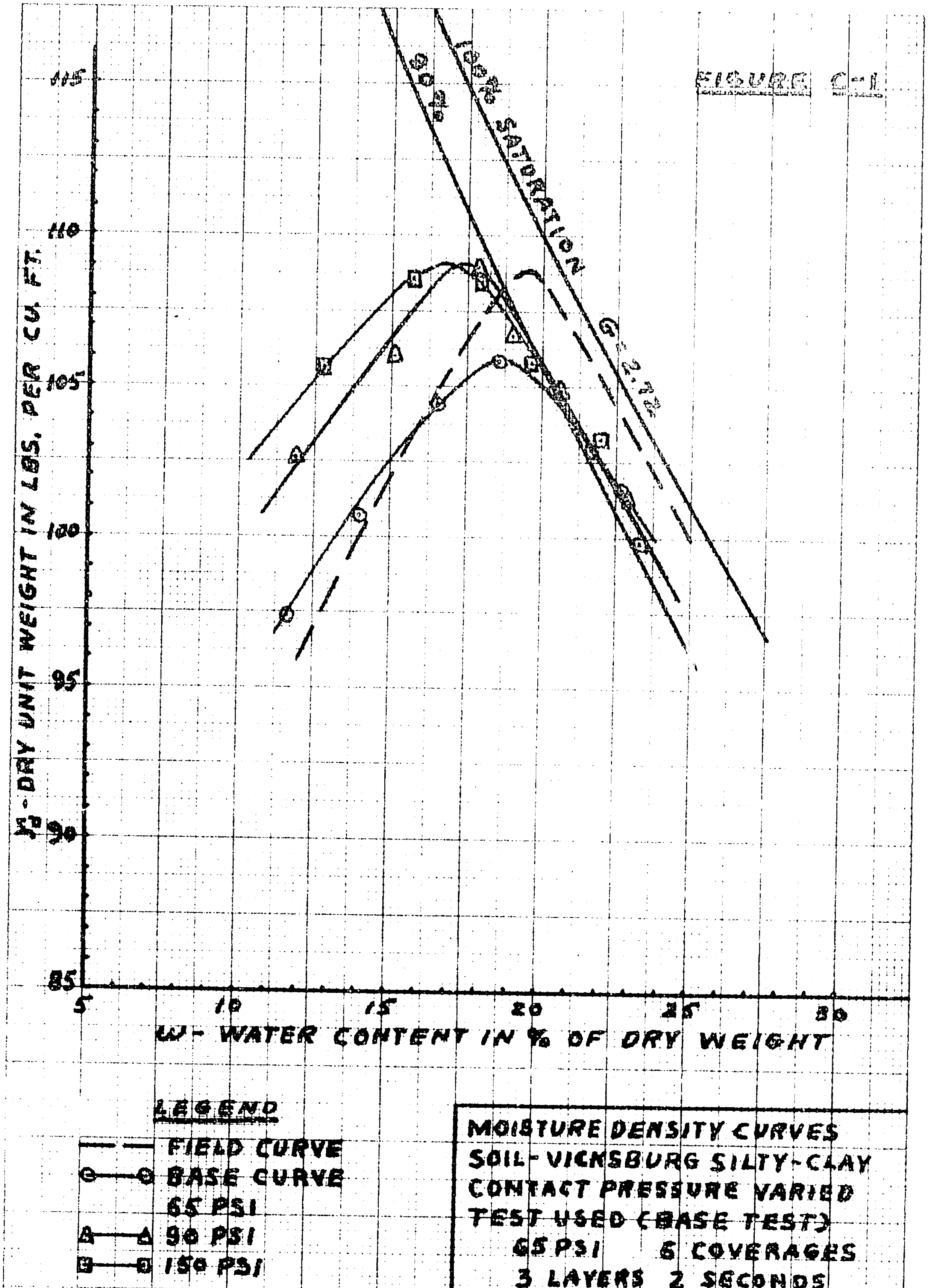
5 layers - compacted thickness 6 inches

4 coverages - 1 roller pass per coverage

1/2 - 1 second - Roller speed 3-5 mph.

Reference (22), Plate 5

FIGURE C-1



MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY-CLAY
CONTACT PRESSURE VARIED
TEST USED (BASE TEST)
65 PSI 6 COVERAGES
3 LAYERS 2 SECONDS
2½ INCH DIAMETER MOLD
⅓ CIRCLE FOOT TAMPER

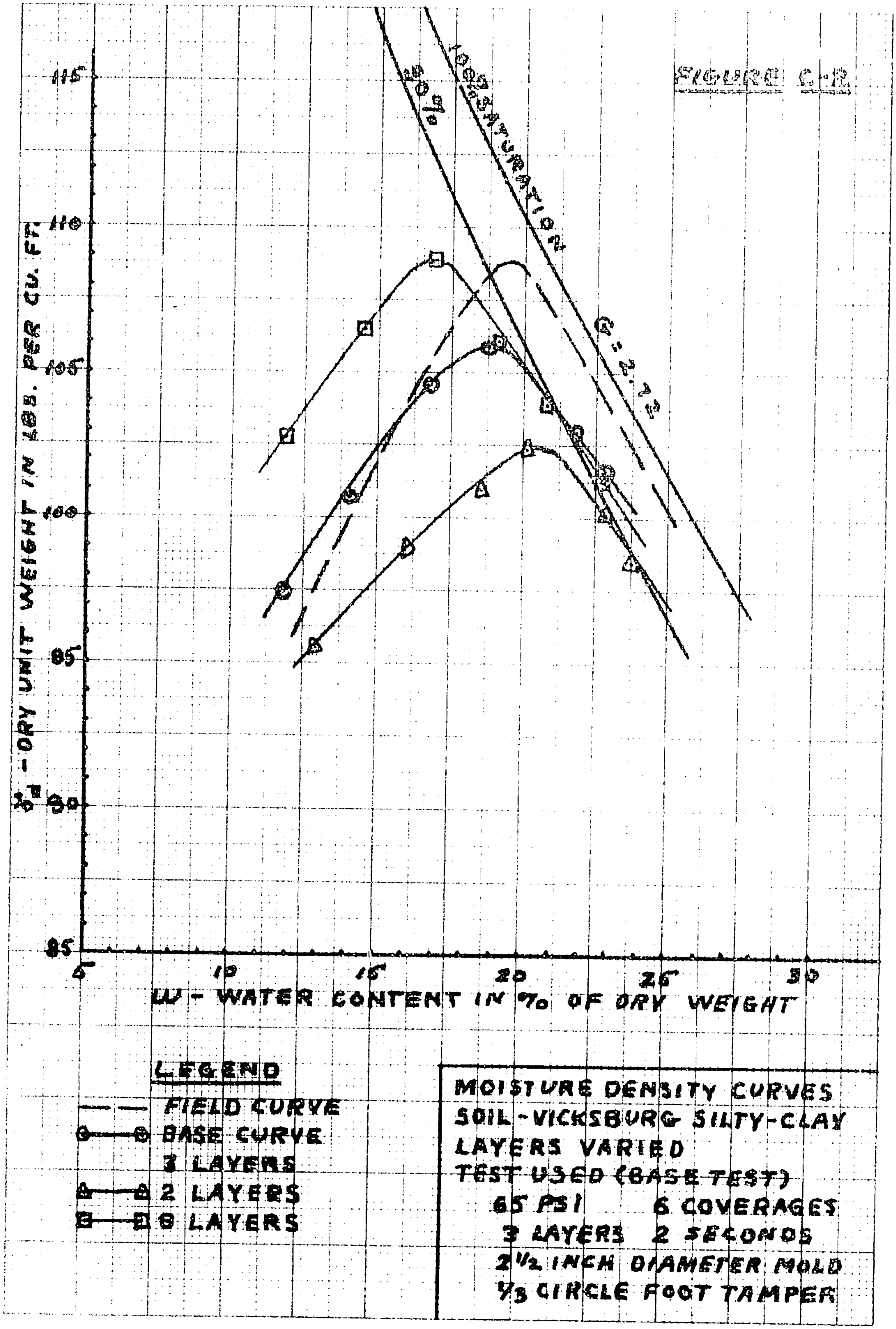
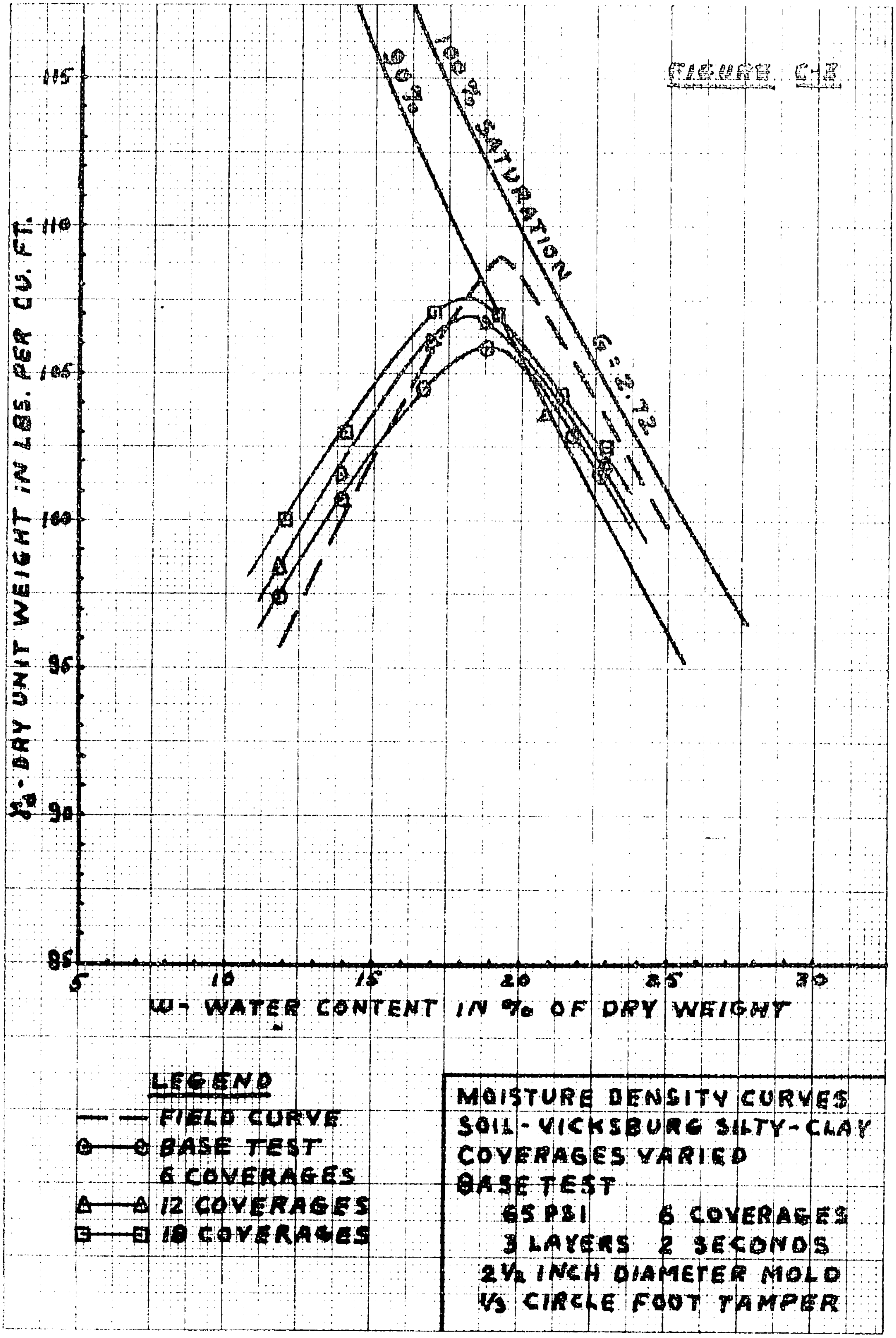


FIGURE C-12

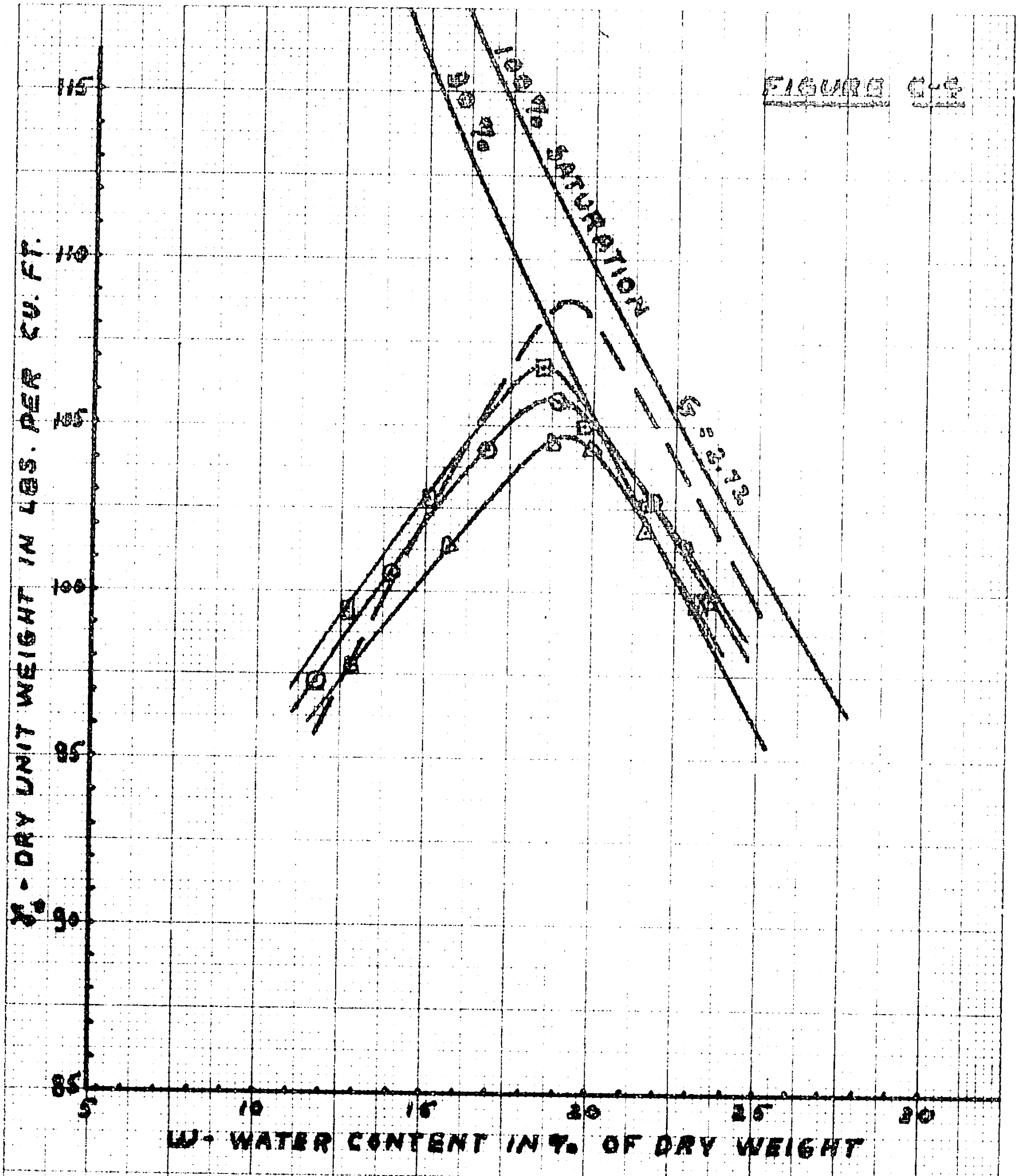
MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY-CLAY
LAYERS VARIED
TEST USED (BASE TEST)
65 PSI 6 COVERAGES
3 LAYERS 2 SECONDS
2½ INCH DIAMETER MOLD
⅓ CIRCLE FOOT TAMPER

FIGURE C-3



MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY-CLAY
COVERAGES VARIED
BASE TEST
65 PSI 6 COVERAGES
3 LAYERS 2 SECONDS
2½ INCH DIAMETER MOLD
⅓ CIRCLE FOOT TAMPER

FIGURE C-4



LEGEND

— — FIELD CURVE
○—○ BASE TEST 2 SECONDS
△—△ ½ SECOND
□—□ 5 SECONDS

MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY - CLAY
TIME VARIED
BASE TEST
65 PSI 6 COVERAGES
3 LAYERS 2 SECONDS
2½ INCH DIAMETER MOLD
⅓ CIRCLE FOOT TAMPER

FIGURE 68

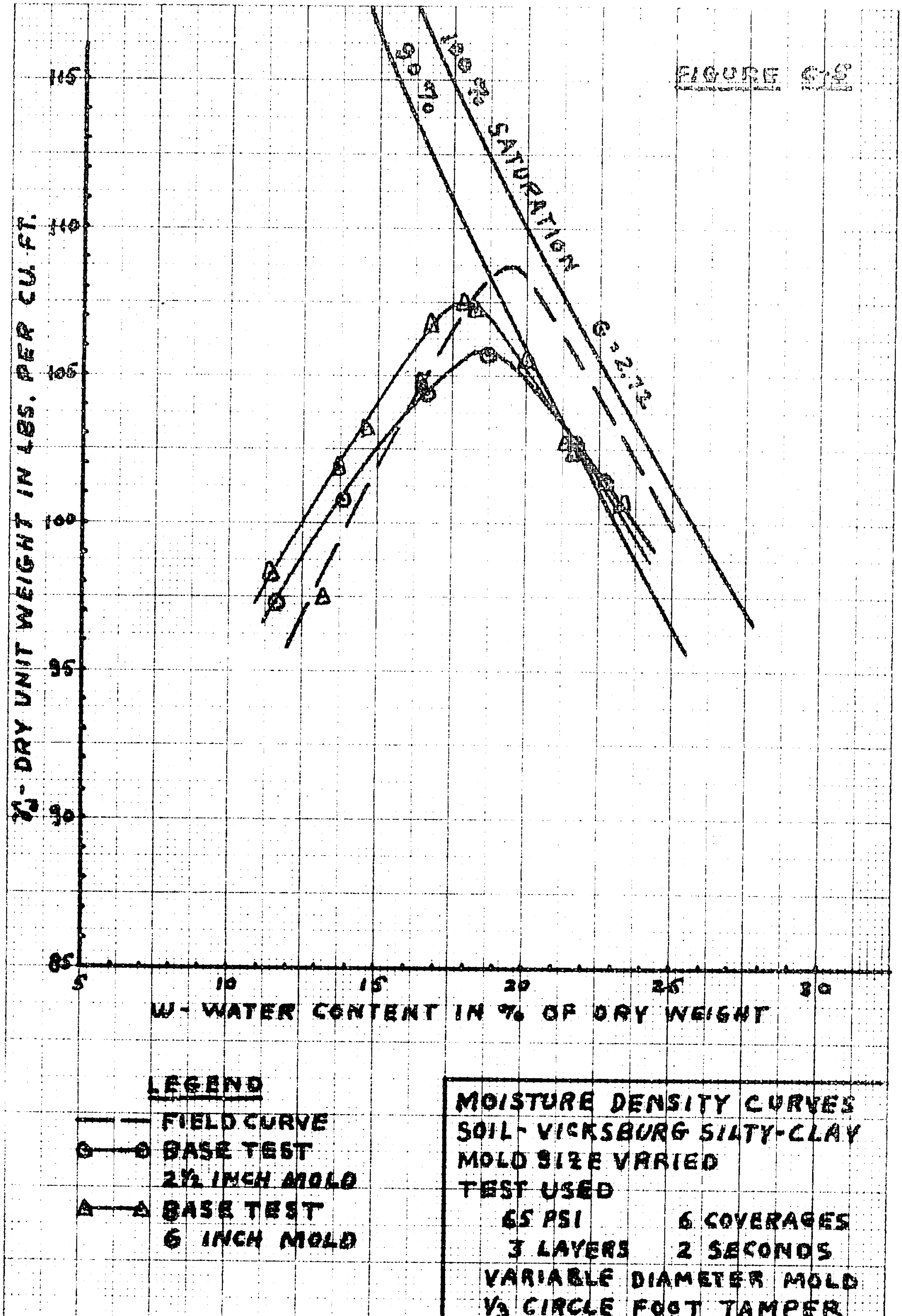
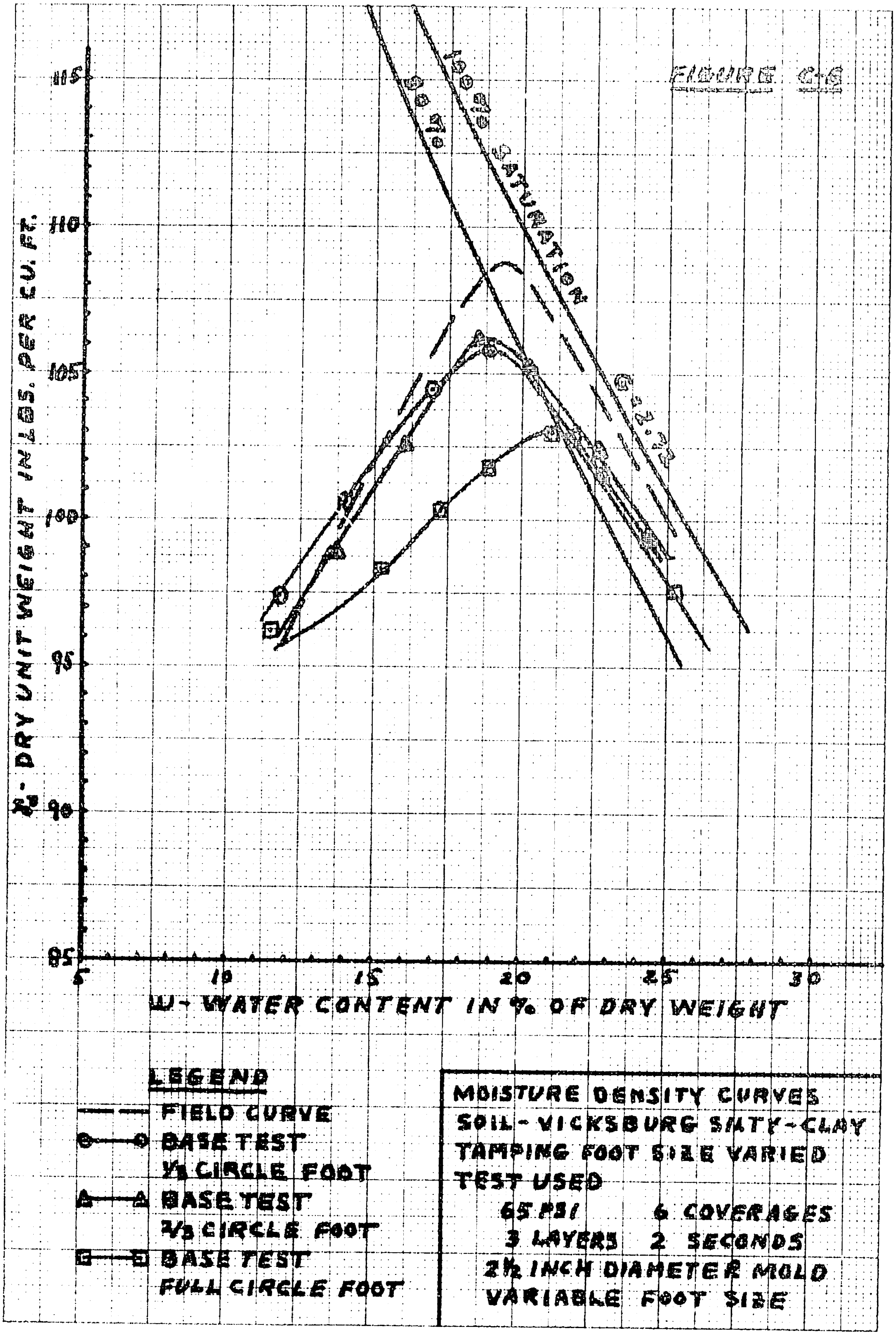
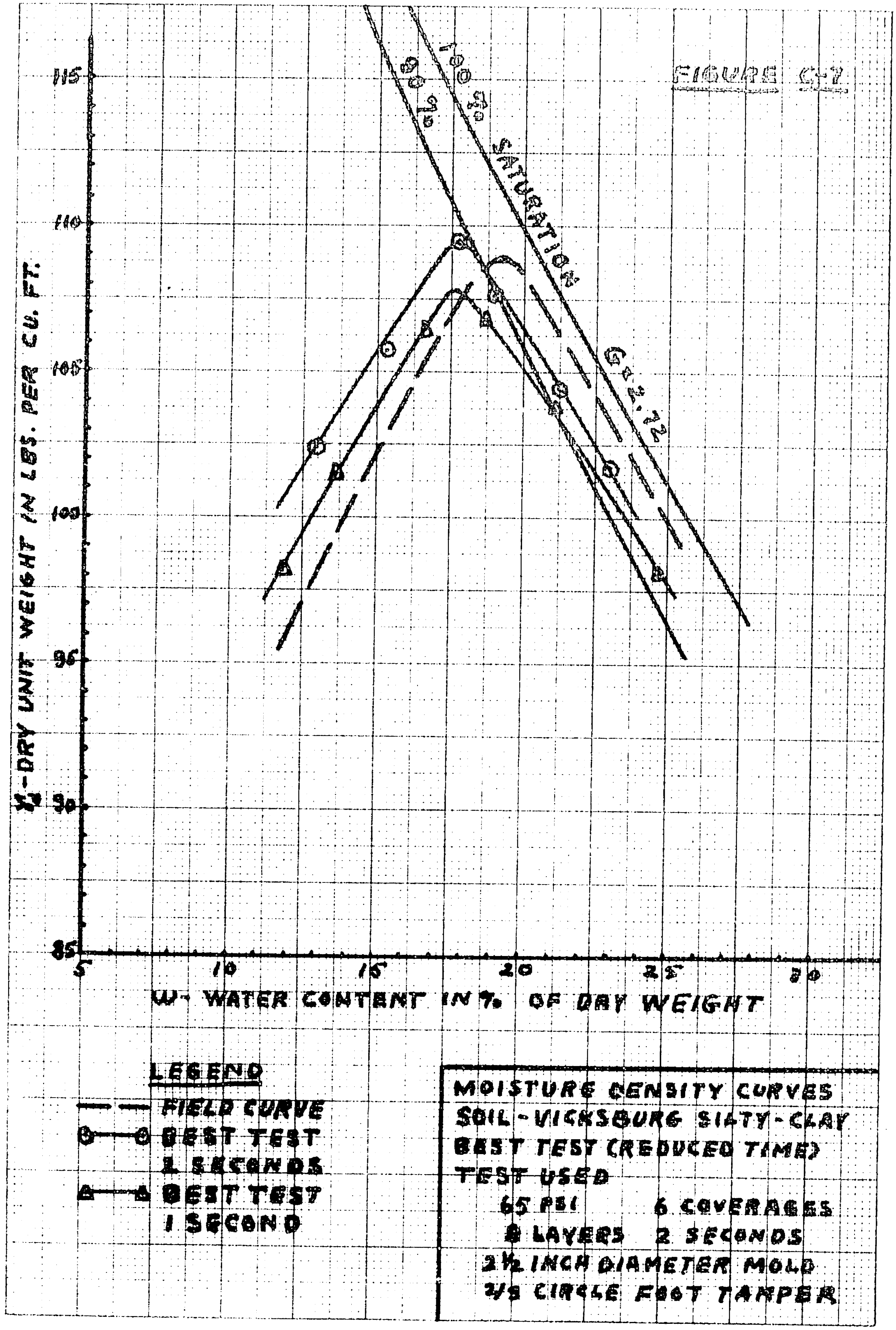

100 % SATURATION
90 %
G = 2.72
γ_d - DRY UNIT WEIGHT IN LBS. PER CU. FT.
115
110
105
100
95
90
85
5
10
15
20
25
30
W - WATER CONTENT IN % OF DRY WEIGHT
LEGEND
FIELD CURVE
BASE TEST 2½ INCH MOLD
BASE TEST 6 INCH MOLD
MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY-CLAY
MOLD SIZE VARIED
TEST USED
65 PSI
6 COVERAGES
3 LAYERS
2 SECONDS
VARIABLE DIAMETER MOLD
1/3 CIRCLE FOOT TAMPER

FIGURE C-6



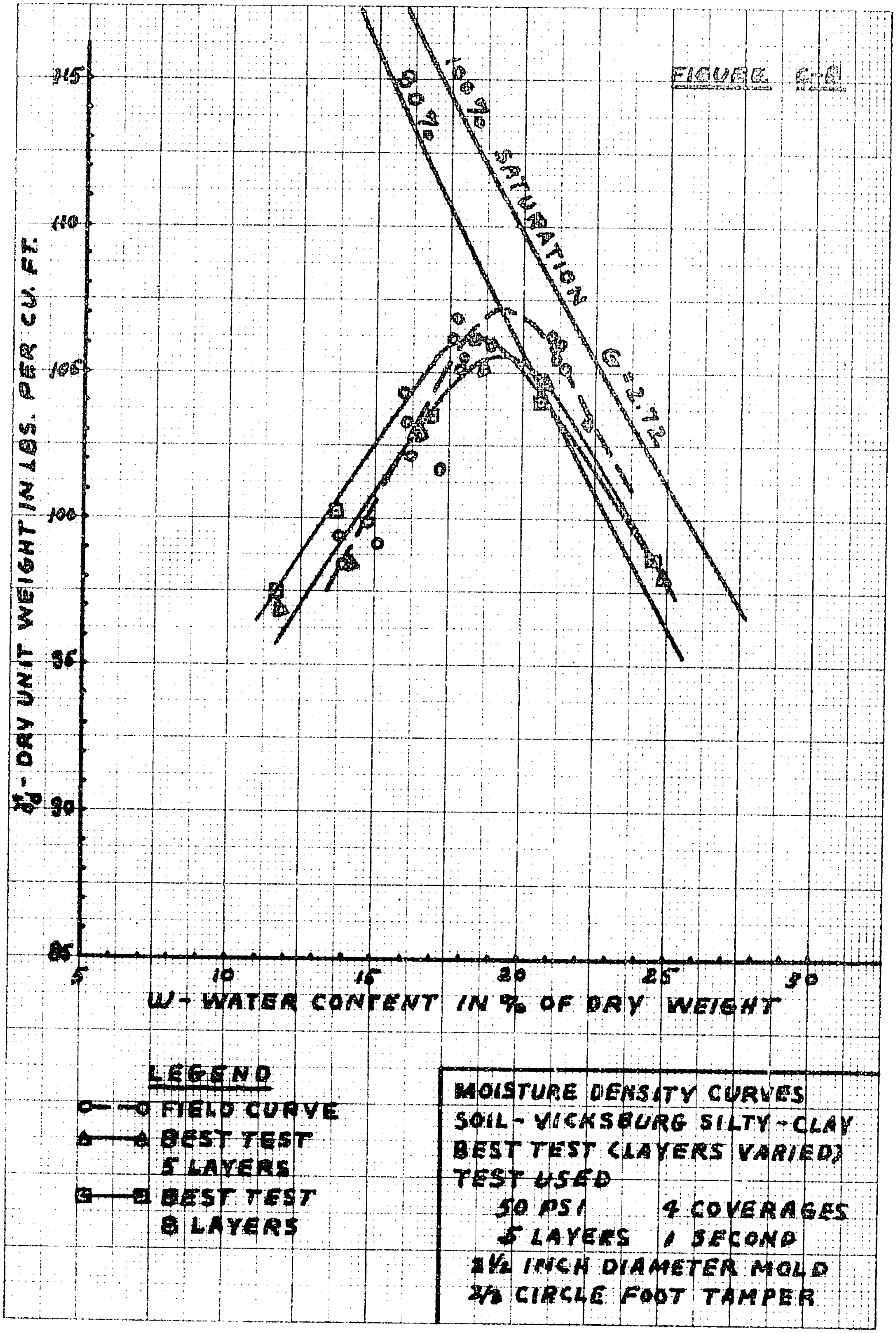
MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY-CLAY
TAMPING FOOT SIZE VARIED
~~TEST USED~~
65 PSI 6 COVERAGES
3 LAYERS 2 SECONDS
2½ INCH DIAMETER MOLD
VARIABLE FOOT SIZE

FIGURE C-7



MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY - CLAY
BEST TEST (REDUCED TIME)
TEST USED
65 PSI 6 COVERAGES
3 LAYERS 2 SECONDS
2½ INCH DIAMETER MOLD
2/3 CIRCLE FOOT TAMPER

FIGURE C-8



MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY - CLAY
BEST TEST (LAYERS VARIED)
TEST USED
50 PSI 4 COVERAGES
5 LAYERS 1 SECOND
2½ INCH DIAMETER MOLD
⅔ CIRCLE FOOT TAMPER

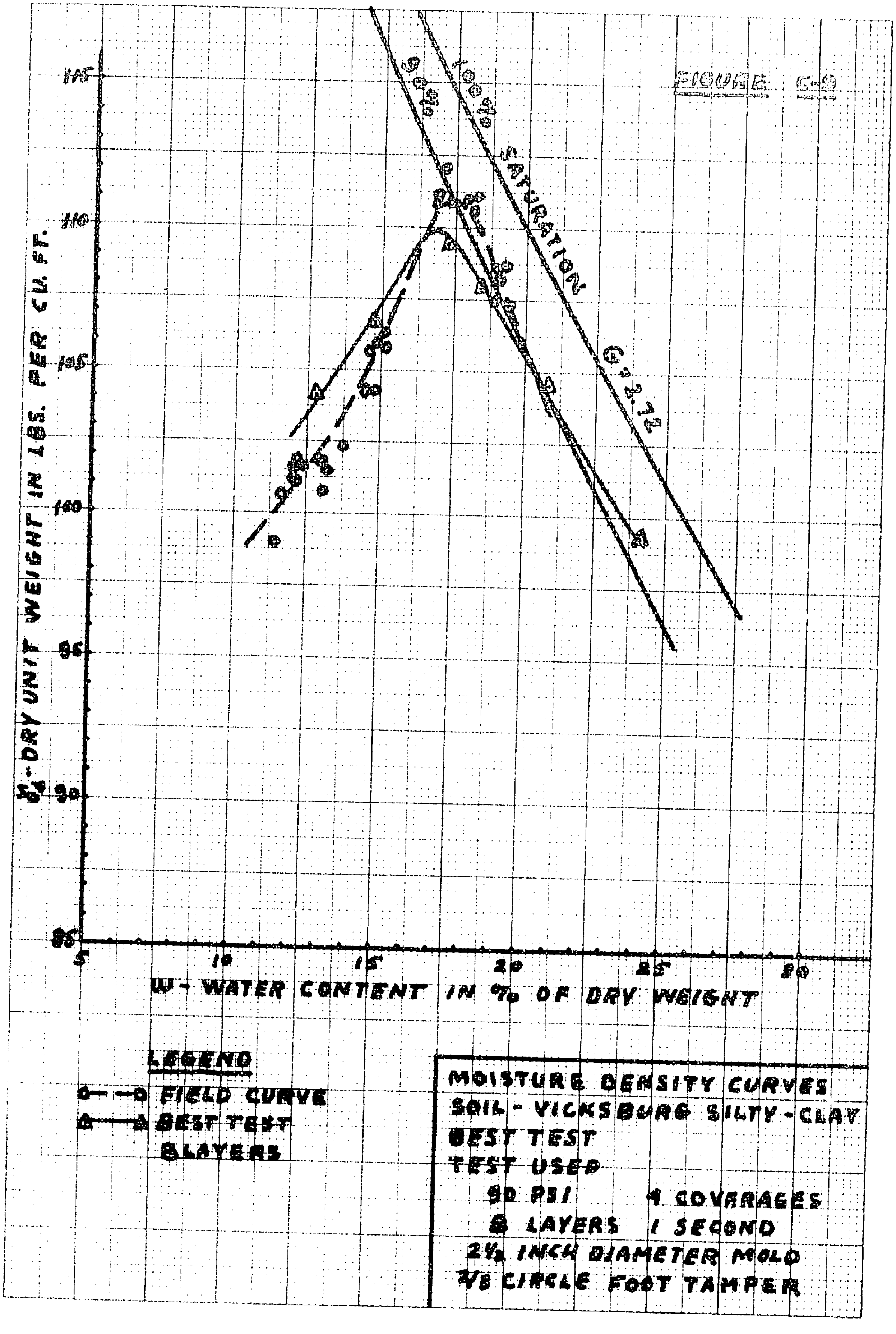
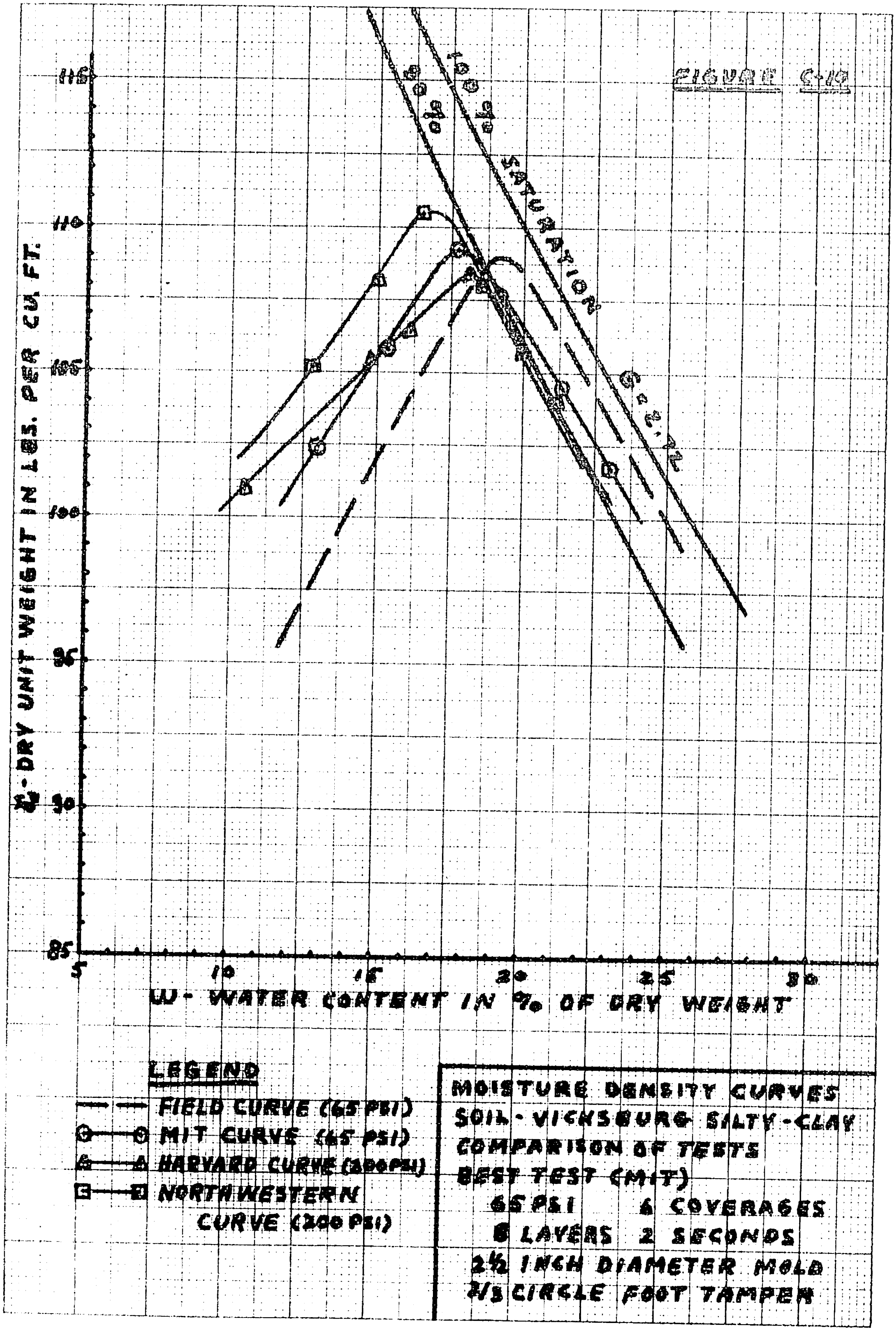


FIGURE 6-9

γd - DRY UNIT WEIGHT IN LBS. PER CU. FT.
115
110
105
100
95
90
85
5
10
15
20
25
30
W - WATER CONTENT IN % OF DRY WEIGHT
90%
100%
SATURATION
G=2.72
LEGEND
o—o FIELD CURVE
△—△ BEST TEST
8 LAYERS
MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY-CLAY
BEST TEST
TEST USED
90 PSI
4 COVRAGES
8 LAYERS
1 SECOND
2½ INCH DIAMETER MOLD
⅔ CIRCLE FOOT TAMPER

FIGURE C-19


115
110
105
100
95
90
85
5
10
15
20
25
30
γd - DRY UNIT WEIGHT IN LBS. PER CU. FT.
ω - WATER CONTENT IN % OF DRY WEIGHT
90 %
100 %
SATURATION
G = 2.72
LEGEND
FIELD CURVE (65 PSI)
MIT CURVE (65 PSI)
HARVARD CURVE (200 PSI)
NORTHWESTERN CURVE (200 PSI)
MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY-CLAY
COMPARISON OF TESTS
BEST TEST (MIT)
65 PSI 6 COVERAGES
6 LAYERS 2 SECONDS
2½ INCH DIAMETER MOLD
1/3 CIRCLE FOOT TAMPER

APPENDIX - PART D

TEST PROGRAM DATA

DENSITY STUDY

Note: See Chapter V, discussion of density study. Data is presented herein on the examination of variation of density with depth of sample. Curves for these data however, are not included in the report since the laboratory procedures used were found to be of such low accuracy.

MOISTURE - DENSITY CURVE TEST DATA

TOP AND BOTTOM OF SAMPLE DENSITY TEST (CASE I) *

TABLE D-1

TEST USED	TEST DATA Entire		Top		Bottom	
	w	γ_d	w	γ_d	w	γ_d
65 psi	12.9	98.0	12.6	102.6	13.1	93.5
3 layers	15.6	100.1	15.5	103.0	15.8	89.0
6 coverages	18.1	104.6	18.2	107.8	18.0	101.5
5 sec	19.8	104.9	19.9	108.5	19.8	101.0
2 1/2" mold	21.4	103.9	21.3	105.9	21.5	101.9
2/3 foot	23.9	100.4	24.0	102.5	23.8	98.6

* Note - This test was conducted to determine whether or not the density was different in the top and bottom of the sample. The sample was extended approximately half way and cut off. Then densities and water contents were computed for top and bottom portions. The sample in Case I was extruded opposite to the direction of application of the compactive effort.

TOP AND BOTTOM OF SAMPLE DENSITY TEST (CASE II) **

TABLE D-2

TEST USED	TEST DATA Entire		Top		Bottom	
	w	γ_d	w	γ_d	w	γ_d
65 psi	12.7	97.7	12.8	96.7	12.6	98.6
3 layers	15.8	99.8	15.8	100.2	15.9	99.5
6 coverages	18.2	105.1	18.2	105.8	18.2	104.3
5 sec	20.0	105.1	20.0	102.7	20.0	107.4
2 1/2" mold	21.6	104.0	21.6	104.2	21.7	103.3
2/3 foot	24.0	99.0	24.3	96.6	23.8	101.0

** Note - This test was conducted in the same manner as Case I, but the sample was extruded in the same direction as the application of compactive effort. The purpose of the test was to determine the effect of the extruder on densities of top and bottom of the sample.

MOISTURE - DENSITY CURVE TEST DATA

SPLIT MOLD DENSITY TEST (CASE III) *

TABLE D-3

TEST DATA

TEST USED	Entire **		Top		Middle		Bottom	
	w	γ_d	w	γ_d	w	γ_d	w	γ_d
65 psi	13.7	99.0	13.4	93.2	13.5	102.2	14.2	101.2
3 layers	16.0	102.6	16.3	100.9	16.0	103.7	15.9	103.6
6 coverages	18.7	106.2	18.7	106.3	18.6	110.0	18.7	103.4
2 sec	20.3	105.2	20.1	103.2	20.6	108.8	20.4	104.0
2 1/2" mold	22.7	102.5	22.7	101.4	22.5	104.3	22.9	102.5
2/3 foot	29.2	99.3	24.2	95.8	28.2	101.2	24.2	100.3

* Note - This test was run using the regular small mold 2 1/2" in diameter and 3" deep, but the mold was sseperated into three pieces, each 1" deep. A water content and density determination was made for the entire sample and for each of the three sections, top, middle, and bottom.

** Note - This is the same data as that given in Table C-6 for the base test with 2/3 circle foot tamper since the tests were run concurrently.

POROUS STONE TEST (CASE IV) ***

TABLE D-4

TEST DATA

TEST USED	Entire Sample	
	w	γ_d
65 psi	13.1	99.2
3 layers	15.7	103.8
6 coverages	19.1	106.8
2 sec	23.0	100.6
2 1/2" mold		
2/3 foot		

*** Note - This test was conducted using a 3/8" thick porous stone in the bottom of the small mold. It's purpose was to determine what effect if any, drainage had on density.

MOISTURE - DENSITY CURVE TEST DATA

CENTER OF SAMPLE DENSITY TEST (CASE V) *

TABLE D-5

TEST USED	Entire Sample **		Center of Sample	
	w	γ_d	w	γ_d
65 psi	11.5	98.5	11.5	101.5
3 layers	13.9	102.1	13.9	104.0
6 coverages	16.5	104.9	16.5	109.0
2 sec	18.3	107.5	18.3	111.1
6" Mold	21.4	102.5	21.5	105.1
1/3 foot	23.3	100.7	23.0	97.4

TEST DATA

* Note - This test was conducted to determine if the density in the center of the sample differed from the entire sample. Oil was used to determine the volume of the soil dug from the bottom center of the large mold.

** Note - This is the same data as that given in Table C-5 for the base test large mold (2^{nd} run). The tests were run concurrently.

CENTER OF SAMPLE DENSITY TEST (CASE VI) ***

TABLE D-6

TEST DATA

TEST USED	Entire Sample		Center of Sample	
	w	γ_d	w	γ_d
65 psi	12.7	101.2	12.7	99.8
8 layers	15.3	105.8	15.3	104.2
6 coverages	18.4	109.0	18.4	107.5
2 sec	19.6	107.8	19.6	107.1
2 1/2" mold	22.0	104.2	22.0	105.1
2/3 foot	23.8	101.5	23.8	102.0

*** Note - This test was conducted to determine if the density in the center of the sample differed from the entire sample. Oil was used to determine the volume of the center of the sample from the small mold (2 1/2" Diameter).

MOISTURE DENSITY CURVE TEST DATA

SPECIAL NOTE (FIELD DATA)

1. The following variables were used to produce the field curves shown in Figs. D-1 through D-6:

Rubber Tired Roller

65 psi - average contact pressure
8 layers - compacted thickness 6 inches
6 coverages - 1 roller pass per coverage
1/2 - 1 second - Roller speed 4-6 mph.

Reference (17), Figure 17

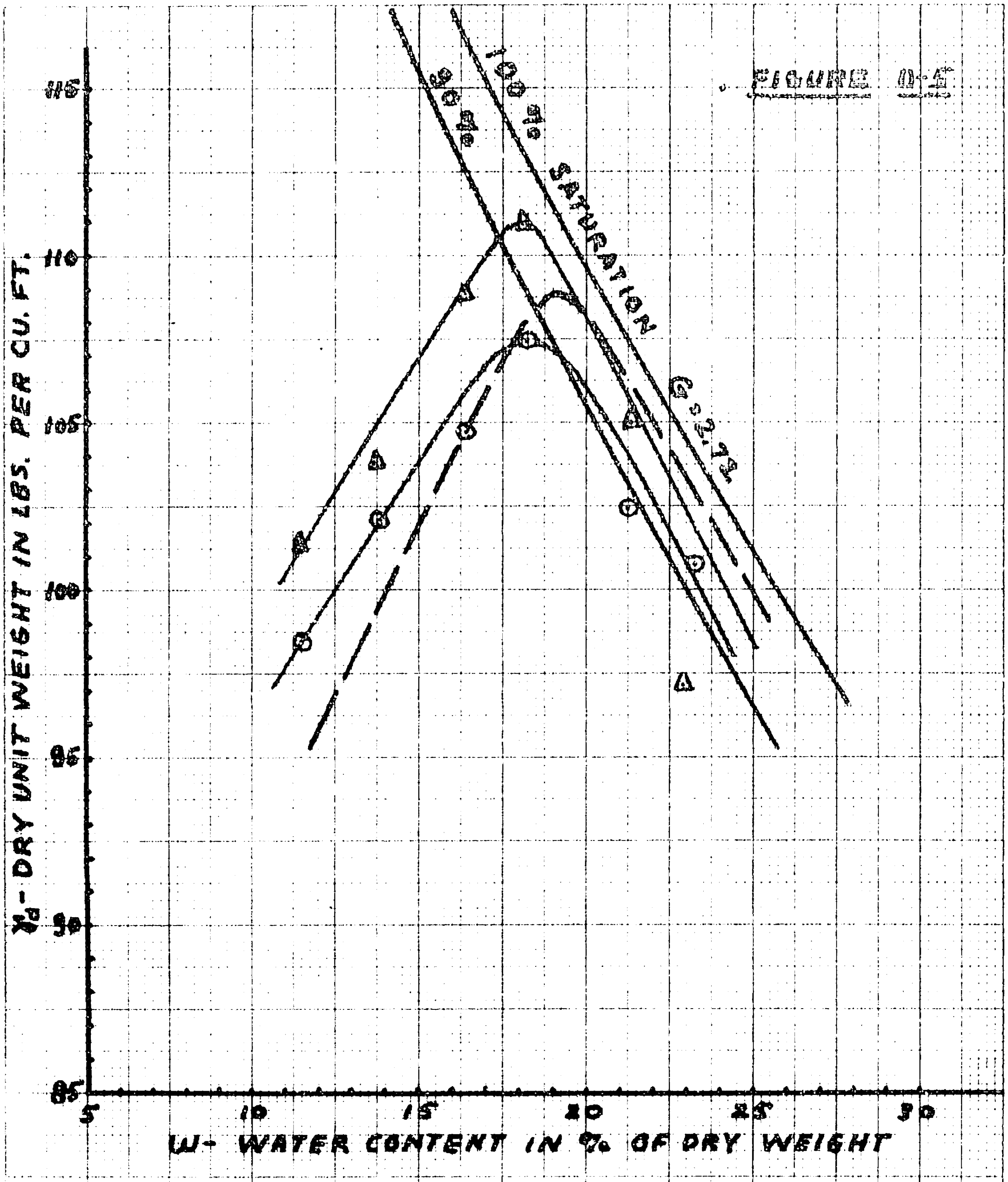


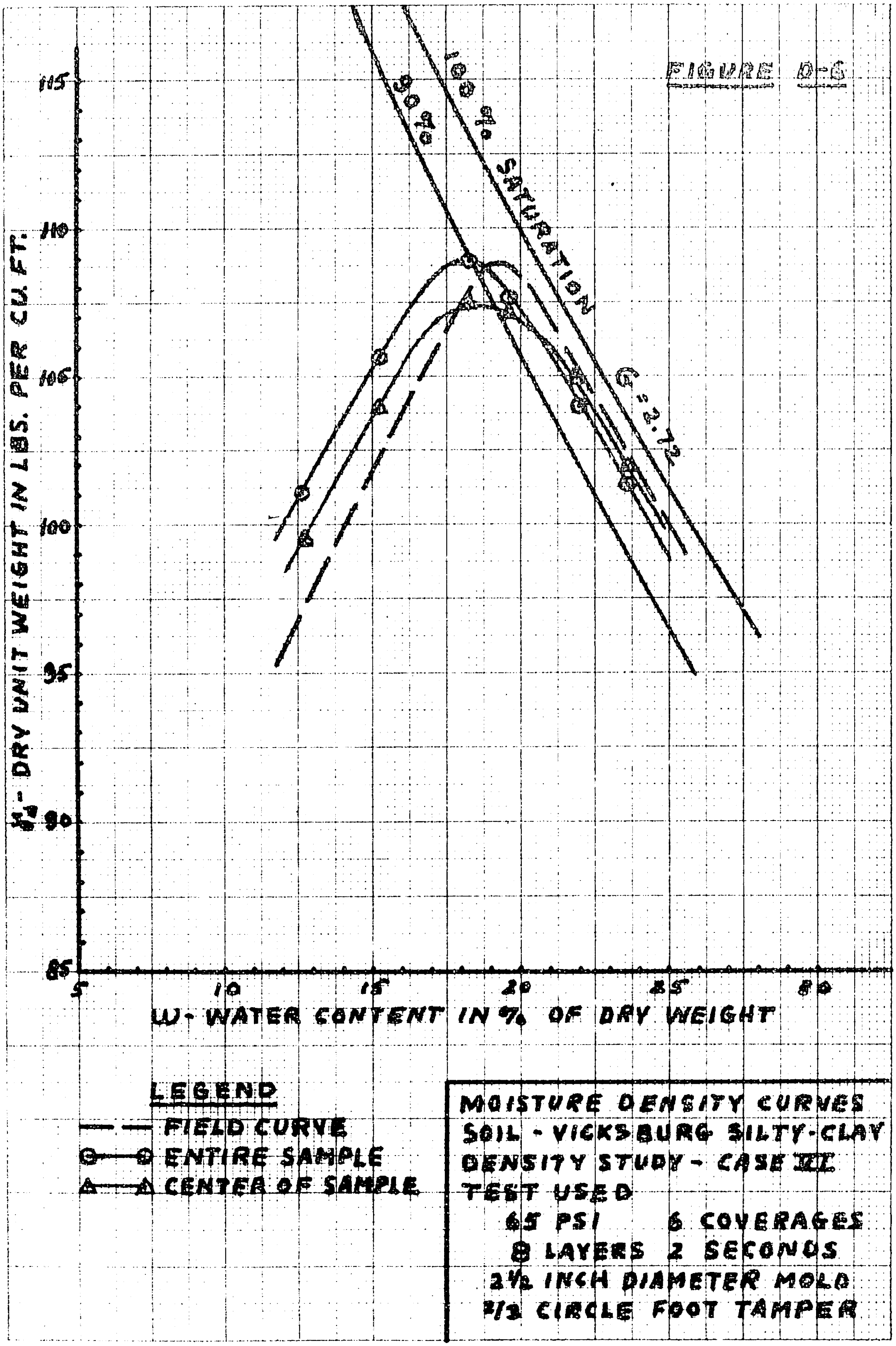
FIGURE II-5

LEGEND

— — FIELD CURVE
○—○ ENTIRE SAMPLE
△—△ CENTER OF SAMPLE

MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY - CLAY
DENSITY STUDY - CASE V
TEST USED
65 PSI 6 COVERAGES
3 LAYERS 2 SECONDS
6 INCH DIAMETER MOLD
1/3 CIRCLE FOOT TAMPER

FIGURE D-6



MOISTURE DENSITY CURVES
SOIL - VICKSBURG SILTY-CLAY
DENSITY STUDY - CASE II
TEST USED
65 PSI 6 COVERAGES
8 LAYERS 2 SECONDS
2½ INCH DIAMETER MOLD
⅔ CIRCLE FOOT TAMPER

APPENDIX

PART E

REFERENCES

REFERENCES

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