FINAL REPORT

For the Florida Department of Transportation

Laboratory Simulation of Field Compaction Characteristics

(Phase I)

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by

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METRIC CONVERSIONS

inches = 25.4 millimeters

feet = 0.305 meters

square inches = 645.1 millimeters squared

square feet = 0.093 meters squared

cubic feet = 0.028 meters cubed

pounds = 0.454 kilograms

poundforce = 4.45 newtons

poundforce per square inch = 6.89 kilopascals

pound per cubic inch = 16.02 kilograms per meters cubed

DISCLAIMER

"The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Department of Transportation or the U.S. Department of Transportation. This publication is prepared in cooperation with the State of Florida Department of Transportation and the U.S. Department of Transportation."

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PROBLEM STATEMENT

Fill materials are used in almost all roadway construction projects. When fill materials are used, the engineering properties of the soil need to be improved by compacting it. The direct consequence of soil compaction is densification, which in turn results in higher strength, lower compressibility, and lower permeability. Most of construction specifications for fill materials are based on laboratory compaction tests. These laboratory compaction tests are designed to represent the highest degree of compaction that can reasonably be achieved in the field. The most common of these laboratory tests are the standard and modified Proctor tests. Both of these tests utilize impact compaction, although impact compaction shows no resemblance to any type of field compaction and is ineffective for granular soils. Since the development of the Proctor tests, there have been dramatic advances in field compaction equipment. Therefore, the Proctor tests no longer represent the maximum achievable field density.

OBJECTIVES

The primary objectives of this project included a survey of current field compaction equipment, laboratory investigation of compaction characteristics, field study of compaction characteristics, and laboratory simulation of field compaction characteristics. The findings from the laboratory and compaction programs were used to establish preliminary guidelines for a suitable laboratory compaction procedure.

FINDINGS AND CONCLUSIONS

The findings and conclusions based on the analysis of this experimental study are summarized below.

1. Numerous tests have shown that impact compaction is not an adequate procedure for compacting pure sands in the laboratory. The standard and modified Proctor test procedures, AASHTO T90 and T180, respectively, were not developed for use with cohesionless soils.
2. Three field tests had shown that with the advent of advanced earthmoving and compaction field equipment, the AASHTO T90 and T180 test procedures no longer represented the maximum achievable field dry unit weights for A-3 sands. Dry unit weights substantially greater than the modified AASHTO maximum dry

density were achieved in the field with a reasonable number of passes when using conventional vibratory compaction equipment on sandy soils when the in-place moisture content was less than or equal to the optimum moisture content corresponding to the field compactive effort.

3. The optimum moisture content corresponding to the field compactive effort was likely less than the modified AASHTO optimum moisture content when sand fill was compacted by more than 3 passes of a conventional vibratory compactor.
4. In the field, compaction after 8 passes of conventional vibratory compaction equipment has little effect on the dry unit weight.
5. Gyratory compaction was more reliable than impact compaction when compacting pure sands in the laboratory.

CHAPTER 1

INTRODUCTION

1.1 Background

Fill materials are used in almost all roadway construction projects. When fill materials are used, the engineering properties of the soil need to be improved by compaction. The primary benefit of compacting a soil is to increase its strength. Several types of machinery are used to compact soils in the field. These include sheepsfoot rollers (also known as padfoot rollers), rubber tire rollers, steel wheeled rollers, and vibratory rollers. Vibratory rollers are primarily used in the compaction of granular soils.

When fill soils are used, they need to be tested in the laboratory first, in order to determine their maximum dry densities and optimum moisture contents (OMC). The maximum dry density determined in the laboratory is often used to specify the required density to which fill should be compacted in the field. Compacting fill at its optimum moisture content is the most economical technique that a contractor can use to achieve the required density of the material. Over the years, several techniques have been developed to compact soils in the laboratory. These include impact, static, kneading, and vibratory compaction. All of these methods are used to determine the density to which soil can be compacted in the field.

Although it has no resemblance to any type of field compaction, impact compaction is by far the most popular laboratory technique. This is largely due to the fact that impact compaction was the first technique to be standardized. As a result, impact compaction tests have been used for decades and a broad base of data exists for comparison. The tests most commonly used in modern construction are the standard and modified Proctor tests. The standard Proctor test was originally developed in the 1930s to represent the highest degree of compaction achievable in the field at that time. The test was modified in the 1940s but has remained unchanged for decades.

1.2 Problem Statement

Previous studies have proved that as the compaction effort increases, the maximum dry density of a soil increases and the optimum moisture content decreases (Selig, 1982). Over the past few decades much heavier earth moving and field compaction equipment has been developed. The fact that this modern compaction equipment produces a far greater compaction effort than the field equipment available in the 1940s demonstrates that the modified Proctor test no longer represents the maximum achievable field density of a soil (point B vs. point C in Figure 1.1). Consequently, compacting fill materials at the optimum moisture content determined using the modified Proctor laboratory test will result in unit weights lower than the maximum achievable density. The inadequacies of the modified Proctor test are compounded when cohesionless (granular) soils are used as fill materials. It is widely known that impact compaction is ineffective on cohesionless soils, yet the method is still widely used to specify the required field density for all types of soils.

As a result of these phenomena , the Florida Department of Transportation (FDOT) and other state transportation agencies have suffered from claims and supplemental agreements to remedy the discrepancies between the laboratory and field compaction results. In response to this trend, the FDOT has funded a research study on the laboratory and field compaction characteristics of soils.

1.3 Scope of Study

The primary objectives of this project were to evaluate field and laboratory compaction characteristics and to further study laboratory compaction techniques such as kneading and/or gyratory compaction, in addition to impact and vibratory compaction, for the laboratory simulation of field compaction. The first step in this process was to evaluate the influence of water content and compactive effort on the compaction characteristics of soils in the laboratory. Also different laboratory compaction techniques were investigated to determine the best way to replicate field compaction. These other techniques included using vibratory and gyratory compaction. While the initial phase of this project investigated these compaction techniques on several subgrade soil types, the bulk of the research concentrated on pure sands, classified A-3 in the AASHTO classification system, due to the inadequacies of current laboratory compaction procedures. After these techniques were investigated in the laboratory, the findings were compared to results from full-scale field tests. Field test sections were constructed using advanced field compaction techniques in order to evaluate the most influential factors for achieving compaction in the field. The field and laboratory results were then analyzed to determine the appropriate procedure to simulate the field compaction effort in the laboratory.

1.4 Report Organization

This report summarizes the results of the study on laboratory and field compaction characteristics. The research presented here is a preliminary investigation that will ultimately be used to develop comprehensive laboratory procedures for compacting soils.

Chapter 1 presents the background, problem statement and objectives of the field and laboratory programs. A brief literature review of previous research in soil compaction is presented in Chapter 2. A discussion on the current state of practice of field compaction as well as a survey of current field compaction equipment are summarized in Chapter 3. A thorough summary of the laboratory study and a presentation of the results are presented in Chapter 4. Chapter 5 is composed of a summary of the field compaction study and the data that resulted from the field tests. Chapter 6 presents the laboratory research that was conducted to simulate the field test results. Finally, conclusions and recommendations of this research study are summarized in Chapter 7.

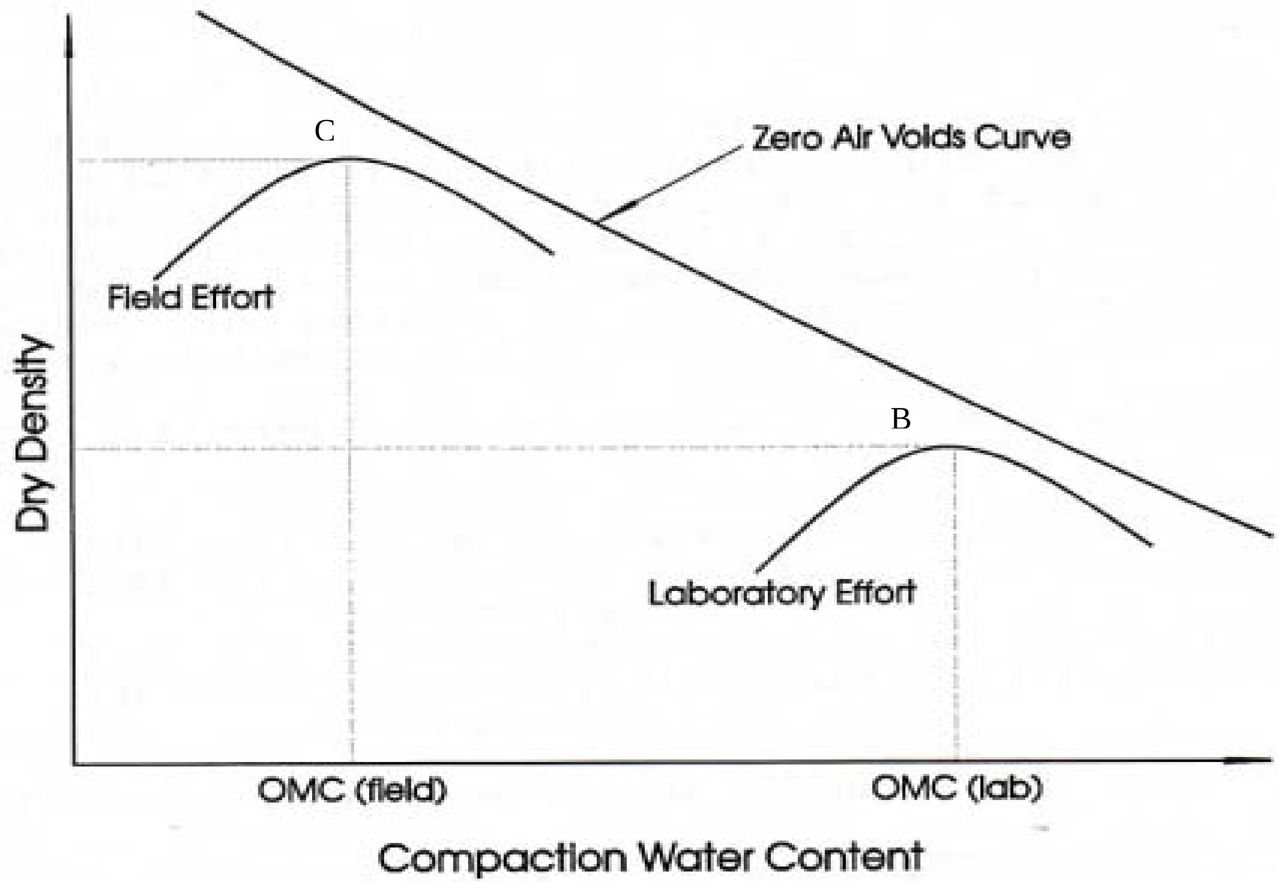


Figure 1.1: Effect of Compactive Effort on the Compaction Curve

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Soil compaction is performed to impart the desired engineering properties to a compacted mass. It is not, in general, practical during the construction of compacted soils to directly specify these desired properties. Rather, the engineer must first specify descriptors of the compacted product, the compactive process, or both that are easy to measure and then the engineer must be able to relate these specifications to the desired properties. The requisite correlations are not simple and continue to challenge engineers seeking the best design.

Although the relationships among compacted properties and the variables of the compaction process are mostly studied directly in the field, this is expensive and time consuming. Accordingly, in the present state of the art, the above relationships are established in the laboratory. But this approach has serious intrinsic limitations, because field compaction is achieved by different modes and at different energy levels than in the laboratory and more variability exists in the field (Essigmann, 1978).

The consequences of bringing a soil to the same compacted density and moisture by different methods of compaction are not clear. Some believe that the soil fabric is strongly influenced by the compaction type and that properties, such as strength, will be peculiar to the method of achieving a given moisture and density, others disagree.

Previous studies have shown that at common moisture-density values, impact and kneading-compacted samples had about the same strength (Essigmann, 1978).

The quality of compacted material is generally specified in terms of dry unit weight, which is usually expressed as a percentage of the maximum dry density achieved in a specific laboratory compaction test. Construction specifications based on this principle are known as “end-result” specifications (Wahls, 1967). There are many laboratory soil compaction procedures. These include the tests based on the Proctor hammer (AASHTO T99 and T180), those using vibratory compaction (ASTM D4253), and procedures based on the Texas State Highway Department gyratory soils press. Details of these test procedures as well as their applications are presented in the following sections. Also, several concerns about construction specifications have emerged as the result of previous field test research. The causes for these concerns are also discussed in this chapter.

2.2 Current Test Procedures

Currently, many published procedures for compacting soils are available. Most of these procedures utilize either impact compaction or vibratory compaction. The most popular test procedures and their uses are discussed in this section.

2.2.1 Impact Compaction

The most common impact compactions tests are the standard and modified Proctor tests, AASHTO T99 and T180, respectively. Developed in the 1930s and 1940s, these tests were the first to be standardized and, as a result, a broad base of data exists for comparison. One downfall of the Proctor tests is that impact compaction has proved to be relatively ineffective for the compaction of noncohesive soils because the material is displaced under the hammer, and consequently low-density values are obtained (Forssblad, 1967). Despite this fact, the majority of states use these test procedures in their construction specifications.

Standard Proctor Compaction Procedure

This test procedure covers laboratory compaction procedures used to determine the relationship between water content and dry unit weight of soils compacted in a 4 or 6 in. diameter mold with a 5.5 lb. hammer dropped from a height of 12 in. producing a compactive effort of 12,400 ft-lb/ft^3. A soil at a selected water content is placed in three layers into a mold of the given dimensions, with each layer compacted by 25 blows of the hammer. The resulting dry unit weight is then determined. This procedure is repeated for a sufficient number of water contents to establish a relationship between the dry unit weight and the water content of the soil. This test procedure applies only to soils that have 30% or less by weight of particles retained on the 3/4 in. sieve. Generally a well-defined maximum dry unit weight will be produced for non-free draining soils. If this test method is used on free draining soils, the maximum unit weight may not be well defined and can be less than that obtained using the ASTM test procedure D 4253 (Maximum Index Density and Unit Weight of Soils Using a Vibratory Table, see section 2.2.2).

Modified Proctor Compaction Procedure

This test method covers laboratory compaction procedures used to determine the relationship between water content and dry unit weight of soils compacted in a 4 or 6 in. diameter mold with a 10 lb. hammer dropped from a height of 18 in. producing a compactive effort of 56,000 ft-lb/ft^3. Five layers of soil at a selected water content are placed into a mold of the given dimensions, with each layer compacted by 25 blows of the hammer. The resulting dry unit weight is then determined. This procedure is repeated for a sufficient number of water contents to establish a relationship between the dry unit weight and the water content of the soil. This test procedure applies only to soils that have 30% or less by weight of particles retained on the 3/4 in. sieve. Generally a well-defined maximum dry unit weight will be produced for non-free draining soils. As with the standard Proctor test procedure, if this test method is used on free draining soils the maximum unit weight may not be well defined, and can be less than that obtained using the ASTM test procedure D 4253.

2.2.2 Vibratory Compaction

For many cohesionless free draining soils, impact compaction does not yield consistent results. As a result, several test procedures have been developed using vibratory compaction. These test procedures produce more consistent results than impact compaction, for the compaction of granular soils. Vibratory compaction also provides a better correlation between the field and the laboratory, since most field compaction is performed with vibratory compaction equipment. The most common laboratory test that utilizes vibratory compaction is the ASTM D 4253, Maximum Index Density and Unit Weight of Soils Using a Vibratory Table, test procedure. Since the development of the ASTM test, several alternative methods have been developed, but none have received wide spread acceptance. One of these alternatives was a vibratory compaction procedure developed by the Concrete and Soil Laboratory of AB Vibro-Verken, Solna, Sweden in the 1960s. This compaction method utilized a vibrating tamper to compact soils. The developers of this procedure claimed that the results obtained during the compaction of cohesionless soils were similar to those obtained by the modified Proctor impact compaction test. This claim detracted from the validity of this procedure because the modified Proctor test is not suitable for round noncohesive soils due to material that is displaced under the compaction hammer. No other proposed method of vibratory compaction has proved to be as suitable as the ASTM D 4253 test procedure.

Maximum Index Density and Unit Weight of Soils Using a Vibratory Table

The ASTM D 4253 test method covers the determination of the maximum index density/unit-weight of cohesionless, free-draining soils using a vertically vibrating table. This test method is applicable to soils that may contain up to 15%, by dry mass, of soil particles passing a No. 200 sieve, provided they still have cohesionless free-draining characteristics. Further, this test method is applicable to soils in which 100%, by dry mass, of soil particles pass a 3 in. sieve. The maximum index density/unit weight of a given free draining soil is determined by placing either oven-dried or wet soil in a mold, applying a 2 lb/in^2 surcharge to the surface of the soil, and then vertically vibrating the mold, soil, and surcharge. The assembly is vibrated using either an electromagnetic, eccentric, or cam-driven vibrating table having a sinusoid-like time-vertical displacement relationship at a double amplitude of vertical vibration of about 0.013 in. for eight minutes at 60 Hz or about 0.019 in. for 10 minutes at 50 Hz. The maximum index density/unit weight is calculated by dividing the oven-dried mass/weight of the densified soil by its volume.

2.2.3 Gyratory Compaction

In recent years, the use of gyratory compactors in the asphalt paving industry has become very common, primarily due to the advent of the SUPERPAVE asphalt design method. Most of the SUPERPAVE gyratory compactors were developed from a manually operated device that was used for many years by the Texas State Highway Department. The Texas Highway Department referred to this device as a gyratory soil press. The soil press was used on both soil and blackbase (asphalt stabilized and emulsion base) materials. This soil press led to the development of the U.S. Army Corps of Engineers Gyratory Testing Machine (GTM) and the GTM in turn led to the development of the current gyratory compactors. During this investigation results show that the new Superpave gyratory compactors can also be used to compact soils in the laboratory. Several reasons can be given for the beneficial use of gyratory compactors. One reason is that gyratory compaction has a stronger resemblance to field compaction than impact compaction does. This means that the internal structure of specimens compacted with a gyratory compactor will show a closer resemblance to that resulting from actual after-construction roadway traffic. A gyratory compactor has the ability to simultaneously apply a vertical load in addition to a self adjusting kneading action which simulates the moving traffic load experienced by a flexible pavement system. In addition to the physical similarities to field compaction, gyratory compactors are generally more precise, effective, and repeatable than impact hammers. Currently there are no standard test procedures for compacting soil with a Superpave gyratory compactor. The only previous research available was conducted using the Texas gyratory soils press or the Army Corps of Engineers GTM.

U.S. Army Corps of Engineers Gyratory Testing Machine

In 1962, the U.S. Army Corps of Engineers (USACE) conducted an investigation into the use of gyratory compaction for determining density requirements for subgrade and base materials. This research took place at the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi, as part of an overall investigation of flexible pavements and soil compaction. The Corps of Engineers found that the AASHTO impact compaction tests proved inadequate in some instances, particularly with cohesionless soils (U.S.A.C.E., 1962). As a result of these inadequacies, excessive settlement was being experienced in the subgrade and/or bases of some flexible pavements. The settlement was due to densification caused by traffic after construction. This indicated that traffic had a greater compacting effect than the compaction achieved during construction. The USACE felt a need for an improved compaction procedure to eliminate these settlement problems.

As stated earlier, the Corps of Engineers had developed their Gyratory Testing Machine (GTM) from a device used by the Texas Department of Transportation. During the initial development of the GTM, the Corps of Engineers undertook a study of the major test variables. During this study, the Corps made several observations. First, the rate of kneading had little or no effect on densification. Additional findings were that increased vertical pressure resulted in a consistent increase in unit weight, that an increased number of revolutions resulted in a consistent increase in unit weight, and that the optimal gyration angle should be between one and two degrees. Information form this early study was used to develop test procedures for both bituminous paving mixtures and soils. Most relevant to this report is the proposed Corps of Engineers test procedure for compacting soils with the GTM. This test procedure was proposed as an alternative to the AASHTO impact compaction tests. The procedure suggested the use of compaction pressures based on the theoretical vertical stresses produced at various depths by the anticipated wheel load. The proposed test procedure is listed below.

A. Obtain a representative sample of the soil or base course material for the proposed pavement system.

B. Select a water content for the test specimen that will be representative of the anticipated water content of the material in the field immediately after construction.

C. Assuming equivalent circular loading for each tire contact area, calculate the theoretical vertical pressure versus depth for the anticipated wheel loading.

D. Thoroughly mix the sample of soil or base material at the selected water content and then compact it in the gyratory compactor for 500 revolutions at a one-degree gyration angle using the vertical pressures corresponding to those computed for several depths beneath the wheel load. Calculate the dry density of the soil or base material on the basis of vertical movement of the compression ram of the gyratory compactor. To calculate the density, it is necessary to know only the weight of the material and the volume of the test mold are needed for various readings of the ram travel. Then prepare a plot of density versus the number of revolutions for each selected depth. On these density versus revolutions curves, mark the point where the next 100 revolutions caused an increase in dry density of only one lb/ft^3. The density at this point will be considered the required construction density for the proposed material at the selected depth.

The Corps of Engineers used this procedure to compare field results with those obtained in the laboratory. They used construction and after-traffic density data that was available from two field test sections. The materials used at the test sections included a limestone aggregate base course and a sand-gravel subbase from Columbus Air Force Base, Columbus, Miss., and a sand-gravel subbase, and a sand subgrade from the channelized traffic test section No. 2 at the Waterways Experiment Station. The USACE used this data to compare the after-traffic densities from the field sections to those densities determined using the gyratory compactor. The after-traffic and gyratory densities were also compared to the modified AASHTO compaction test results as well as the construction densities. The conclusions the Corps of Engineers showed a good correlation between the gyratory computed construction density and the post-construction field density for the four cohesionless subgrade and base materials tested. In addition, they found that the densities obtained using the proposed gyratory test procedure showed a better correlation with the after-traffic densities than those results obtained with the AASHTO compaction test.

2.3 Field Compaction

Several factors need to be considered whenever field operations are conducted. These factors include equipment selection, moisture control, applied compaction energies, and quality control. Further discussion of these factors and their effects on field compaction are provided in this chapter.

2.3.1 Moisture Control

Moisture requirements are often included in construction specifications for embankment and subgrade soils. However most of these requirements are specified in a qualitative manner, leaving the interpretation to the judgement of the inspector. Qualitative statements commonly included in construction specifications are “to the satisfaction of the engineer”, “as required by the engineer”, or “as required for compaction”. These types of specifications give the impression that moisture control is of little concern in the field. This is especially the case for granular materials. These materials may be compacted successfully at a relatively large range of moisture contents, although the materials may experience bulking problems at excessively high water contents (Transportation Research Board, 1990). This reason alone suggests that the modified Proctor laboratory compaction test has little in common with field compaction of granular soils and that the density data obtained from the test does not represent the maximum achievable field compaction.

2.3.2 Field Tests

The undertaking of a comprehensive compaction field test requires a great deal of coordination as well as financial backing. For these reasons there have been very few tests conducted over the years. The U.S. Bureau of Public Roads sponsored one such test, in 1964. The three part study included an evaluation of the state of the art compaction of soil and rock for highway purposes, a fundamental study of properties of soils in the laboratory, and a full scale field test dealing with soil compaction for highway purposes. The field test was conducted by the Illinois Institute of Technology (IIT) Research Institute, from June through October 1965, at Hazelcrest, Illinois (Hampton, 1967).

The objectives of the field test were to determine (1) the desired characteristics of compacted soil, (2) how best to measure and specify the proper compaction, and (3) the effectiveness of various methods of achieving compaction. For the purpose of this report the researchers are most interested in the proper method of specifying compaction. During the field test, several different field compactors were evaluated for several types of soils. During the field test, four different soil types were compacted using four different compactor types (vibratory, pneumatic, sheepsfoot, and segmented pad). Each of the test lifts was compacted with 16 passes of the respective compactor. Density measurements were taken after 2, 4, 8, and 16 passes. The vibratory roller, which is of the greatest relevance to this report, was found to be the most effective for compacting silty sand, subgrade soils. This finding coincides with the fact that a common practice today is to use vibratory rollers on sandy soils.

Another interesting finding was that the maximum density measurements for each compactor type ranged from 89 to 102 percent of the modified Proctor maximum density for each soil. This indicates that the compaction equipment available in 1964 could not achieve densities much higher than the modified Proctor density. This means that in 1964 the modified Proctor compaction test was a reliable method of calculating the maximum achievable field density. The compaction equipment available today has far greater capabilities than the equipment available in 1964. This would indicate that compaction equipment today is capable of reaching densities higher than the modified Proctor densities, and that changes are needed in the construction specifications to coincide with the technological advances of the industry. Also, the majority of the field test strips were compacted dry of optimum, which suggests a difficulty in sustaining the high water contents that are specified by the modified Proctor test.

CHAPTER 3

SURVEY OF CURRENT FIELD OPERATIONS

3.1 Introduction

A survey of the state of practice in field compaction needed to be completed before the field tests could be conducted. Included in the survey reported here was a study of current on-going field compaction techniques for roadway construction as well as an investigation into the field compaction equipment that is most commonly used. Discussions with construction contractors as well as specifications provided by equipment manufacturers were used to determine the appropriate techniques that were to be used during the field tests.

3.2 State of Practice

In order for the field test to yield useful results, the field tests needed to be conducted using practices commonly implemented by contractors. Several factors affecting compaction had to be investigated before the field test could take place. These factors included the type of field compaction equipment used and the layout of the field compaction lifts. Several types of compaction equipment are commonly used for roadway construction. These types include sheepsfoot rollers (also known as padfoot rollers), rubber tire rollers, steel-wheeled rollers, and vibratory rollers. The type of equipment that a contractor selects should be determined by the type of soils encountered. Certain types of compactors work better with some types of soils than with others. In many cases, however, the contractor will use whatever equipment he already owns or has leased.

Whatever equipment the contractor uses must comply with the specification requirements and must be approved by the engineer. Minimum wheel loads and tire pressures for pneumatic rollers and minimum weight for steel wheel rollers are specified, whereas for vibratory drum compactors, a specific frequency range and a minimum dynamic force are usually specified. Length of feet, minimum weight per square inch of cross-sectional area of the tamping feet, and operating speed are specified for sheepsfoot rollers.

Maximum lift thickness should be specified depending on the equipment being used or the project soils, or both. This way, the inspector will know in advance the maximum thickness that the contractor will be allowed to place and compact. The contractor can place thinner lifts if he chooses.

Pneumatic-tire compactors achieve compaction by the interaction of (a) wheel load, (b) tire size, (c) tire ply, (d) inflation pressure, and (e) the kneading action of the rubber tires as they pass over the lift. Pneumatic-tire rollers should be ballasted to meet at least the minimum wheel load.

Vibratory drum compactors develop their compactive effort by vibrations. Four machine features must be known in order to rate vibratory rollers: (a) unsprung drum weight, (b) rated dynamic force, (c) frequency at which the rated dynamic force is developed, and (d) drum width. The contractor or equipment supplier should have these data. Vibratory rollers should operate between 1,100 and 1,500 vpm, and the dynamic force at the operating frequency should be at least 2.5 times the unsprung drum weight (see the manufacturer's literature for the roller). Therefore, by using the machine data and the specification requirements, a range of acceptable frequencies can be determined.

Compaction of granular soils is mostly due to the dynamic force created by a rotating eccentric weight. Vibratory compactors dramatically lose their effectiveness when the vibration is shut off because the compaction is due solely to the static weight of the machine. Satisfactory compaction of thick lifts cannot be accomplished in this case.

When sheepsfoot rollers are used, the criteria for job control can be determined by a test in the field. The feet must penetrate into the loose lift. If they ride on top, the machine is too light and the ballast must be increased. With succeeding passes, the feet should "walk out" of the layer. The number of passes required for the feet to walk out of the layer will then be used to control subsequent layers. If the feet do not walk out, the machine is too heavy and is shearing the soil, or the soil is too wet. The roller should be lightened and a new test should be performed for job control or the soil should be dried.

To be effective, smooth steel wheel rollers should weigh at least 10 tons and exert a minimum force of 300 lb per linear inch of width on the compression faces. These data can usually be obtained by referring to the manufacturer's specifications on the roller. At least eight passes over the lift at a maximum speed of six ft/sec are usually adequate. These rollers may be used on lifts of eight inches or less of compacted thickness (Transportation Research Board, 1990).

Prior to each field test, meetings were conducted with the contractors involved. Through these discussions, contractors concluded that the most common field practice for compacting granular soil was to use a smooth-drum vibratory compactor. This type of compactor is commonly operated at the maximum speed and vibrating frequency. In one case the smooth-drum roller was run in combination with a pad-foot roller (both vibratory). When using this technique, the pad-foot roller would make several passes over the soil and then would be followed by several passes with the smooth-drum roller. The manufacture's specifications for the compactors used during the field tests are listed in section 3.3. Results also show that the most common lift thickness used during compaction of stabilized subgrade or embankment soils was 12 to 18 inches of loose soil (before compaction). The information acquired during these contractor discussions was implemented during the field tests, ensuring that the results would represent typical roadway construction.

3.3 Field Compaction Equipment Specifications

Specifications for the field compaction equipment that was used during the field tests are listed below.

INGERSOLL-RAND SD 100D

Type	Smooth-Drum Vibratory
Operating Weight	22,490 lb
Overall Length	225 in
Overall Width	93 in
Wheel Base	130 in
Drum Diameter	59 in
Vibration Frequency	18.3-31 Hz
Nominal Amplitude-High	0.067 in
Nominal Amplitude-Low	0.033 in
Rated Engine Power	125 hp
Travel Speed	0-7.6 mph

CATERPILLAR CS 563C

Type	Smooth-Drum Vibratory
Operating Weight	24,700 lb
Overall Length	207 in
Overall Width	96 in
Wheel Base	108 in
Drum Diameter	60 in
Vibration Frequency	30 Hz
Nominal Amplitude-High	0.067 in
Nominal Amplitude-Low	0.034 in
Rated Engine Power	132 hp
Travel Speed	0-8 mph

DYNAPAC CA 251 PD

Type	Pad-Foot Vibratory
Operating Weight	25,580 lb
Overall Length	215 in
Overall Width	84 in
Wheel Base	113 in
Drum Diameter	60 in
Number of Pads	150
Height of Pads	4 in
Vibration Frequency	30 Hz
Nominal Amplitude-High	0.064 in
Nominal Amplitude-Low	0.031 in
Rated Engine Power	151 hp
Travel Speed	0-6 mph

All compactors were operated at their maximum speeds and vibration frequencies during the field test. The compaction procedure for each field test was determined by the contractors’ normal methods of operation. The results of these field tests are presented in Chapter 5 of this report.

CHAPTER 4

LABORATORY INVESTIGATION OF COMPACTION CHARACTERISTICS

4.1 Introduction

The first task of this research project was to investigate the current standards for laboratory compaction. The two major factors that affect soil compaction are the moisture content of the soil and the compactive effort that is applied to the soil. These two factors were investigated in order to evaluate their influence during impact compaction. During the preliminary investigation, the modified Proctor test was used as a standard level of compaction. After the modified Proctor compaction curve had been developed for a specified soil, the energy level of the compaction test was increased further. Compaction curves at several energy levels were completed for each soil. These alternate compaction curves were compared to the modified Proctor compaction curve in order to determine the influence of increasing the energy level applied to a soil.

4.2 Soil Materials

Several soil types were used during the initial laboratory investigation. The soils were chosen to represent the types of material that are commonly used for stabilized subgrade in Florida. These soils included a silty sand from Alford City, a clayey sand from Clay County, and a fine sand from Lake City. The basic properties of the soils are listed in Table 4.1.

Table 4.1: Soil Materials for Laboratory Investigation

Location	Visual Description	AASHTO Classification	% Passing No. 200
Alford City	Silty Sand	A-2-4	17.6
Clay County	Clayey Sand	A-2-6	27.5
Lake City	Sand	A-3	4.5

4.2.1 Impact Compaction

As stated earlier in this report, impact compaction is the most common type of laboratory compaction used today. The most popular impact compaction test procedures are the Standard and Modified Proctor tests. The majority of states use results obtained from these two test procedures to specify density requirements for roadway construction. Currently, Florida requires stabilized subgrade to be compacted to 98 percent of the maximum dry density determined from the Modified Proctor test, and embankment materials to be compacted to 100 percent of the maximum Standard Proctor density.

The initial stages of the project began by investigating the current standards for laboratory compaction to determine how changes could be made to improve these existing test standards. The procedure for the Modified Proctor test calls for a 10 pound hammer to be dropped 18 inches, onto a sample, 25 times. This is repeated on five layers of soil in order to fill a mold with a volume of 1/30 ft^3. During the first laboratory tests, the energy level used in the Proctor test was increased in order to develop compaction curves at several energy levels. The energy levels were increased in several ways. The weight of the hammer was increased from 10 lbs. to 15 lbs, the number of blows was increased from 25 to 50, and the number of lifts was increased from five to eight. These changes in the test procedure were used in several combinations. From initial test results it was determined that changing the number of lifts in the test procedure did not result in any significant results that could not be obtained from the other procedural changes. It was determined that further procedural changes should concentrate on changes in the hammer weight and number of blows. After further investigation a decision was made to develop compaction curves using the following procedures: 10 lb. hammer-25 blows (Modified Proctor), 10 lb. hammer-50 blows, 15 lb. hammer-25 blows, 15 lb. hammer-50 blows. Compaction curves at these energy levels were developed for the soils that were listed in section 4.2. These curves can be seen in section 4.3.2. In most cases the maximum density for each soil increased and the optimum moisture content decreased with higher compactive energies. The only exception to this occurred during the compaction of the fine-grained A-3 sand. In this case, increasing the weight of the hammer had little or no effect on the maximum density. The lack of cohesion in pure sands made using impact compaction difficult. When impact compaction is used on round noncohesive soils, the material displaces under the hammer and consequently low density values are obtained. The inability to consistently produce compaction curves for pure sands is a major concern. These sands do not produce a consistent bell-shaped curve and can make determining the optimum water content difficult. The results of these early tests were used to make preliminary decisions on the applicability of impact compaction. The results showed that impact compaction is satisfactory for most soils but not for pure sands (i.e. soils classified as A-3). When dealing with pure sands in the laboratory it is necessary to use other types of compaction in order to determine their maximum densities and optimum moisture contents. Even though impact compaction is useful for many soils, the Modified Proctor test procedure may no longer represent the maximum achievable field density. As can be seen on from the compaction curves, densities much higher than those obtained from the Modified Proctor are achievable in the laboratory. If these densities can be reached in the laboratory then they can be realistically reached in the field.

Table 4.2 Compaction Data of Alford City A-2-4

Water Content	10 lb Hammer, 25 Blows	10 lb Hammer, 50 Blows	15 lb Hammer, 25 Blows	15 lb Hammer, 50 Blows
5.30	122.00			
6.47	124.80			
7.29	126.64			
8.10	128.14			
9.44	126.30			
5.40		126.66		
6.39		129.20		
7.41		130.60		
8.25		130.71		
9.14		127.40		
5.35			126.32	
5.89			129.12	
6.10			130.80	
6.80			132.08	
7.75			130.50	
8.36			129.76	
5.11				131.11
5.74				133.66
6.24				134.49
7.24				134.38
7.90				132.40
8.17				131.09

Table 4.3 Compaction Data of Clay County A-2-6

Water Content	10 lb Hammer, 25 Blows	10 lb Hammer, 50 Blows	15 lb Hammer, 25 Blows	15 lb Hammer, 50 Blows
7.81	121.73			
7.95	122.36			
8.95	124.86			
9.19	125.29			
9.60	127.29			
11.39	123.61			
7.36		125.23		
7.72		126.98		
8.88		130.72		
9.21		130.47		
9.52		129.41		
11.27		124.29		
7.10			128.04	
8.10			130.00	
8.30			129.95	
9.10			129.69	
10.40			126.55	
7.30				132.20
8.30				133.16
8.60				132.60
8.80				132.50
11.00				124.72

Table 4.4 Compaction Data of Lake City A-3

Water Content	10 lb Hammer, 25 Blows	10 lb Hammer, 50 Blows	15 lb Hammer, 25 Blows	15 lb Hammer 50 Blows
8.80	104.59			
10.07	104.81			
10.93	105.13			
11.94	104.98			
12.42	105.15			
8.84		106.20		
9.84		105.85		
10.95		106.37		
11.62		106.38		
12.47		106.55		
8.93			103.65	
9.85			104.45	
11.08			104.76	
11.52			104.89	
13.03			105.26	
8.62				105.85
9.85				105.88
11.00				106.18
11.22				106.07
11.65				107.33
11.96				106.96
13.41				106.39

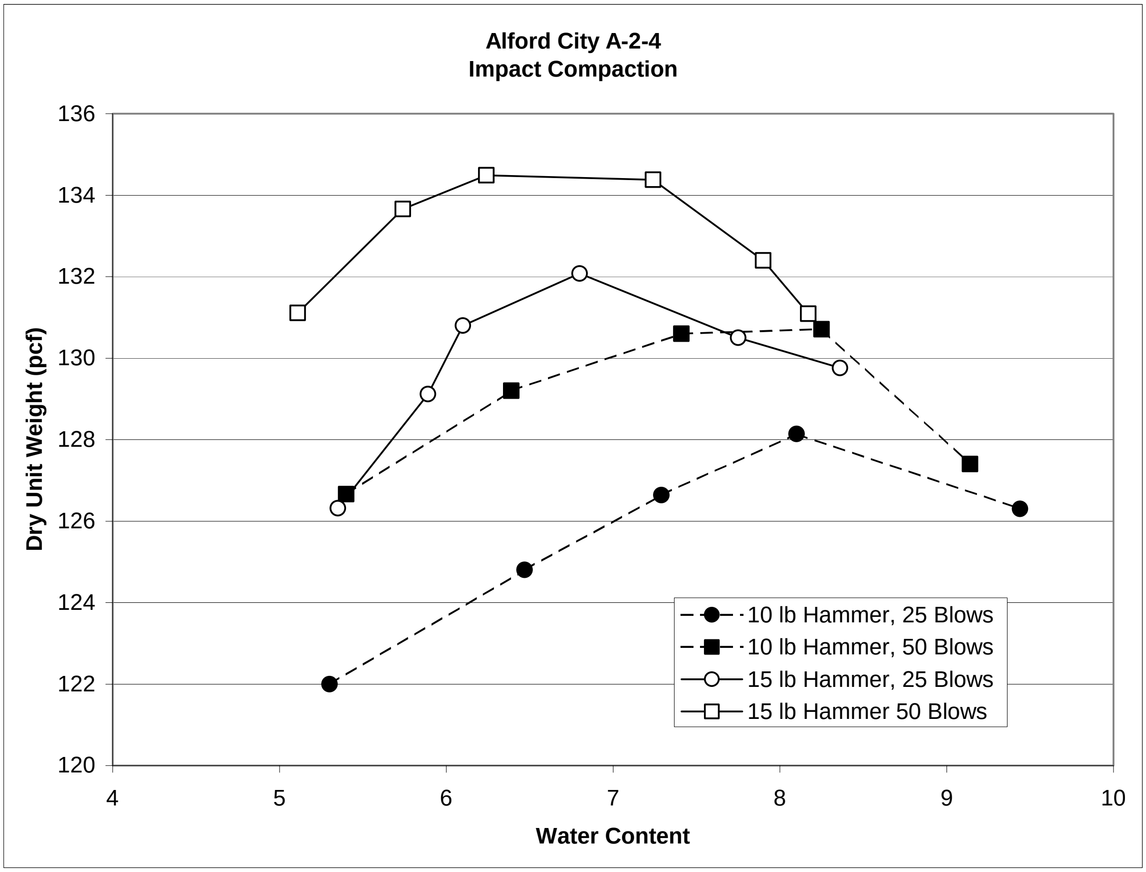


Figure 4.1 Alford City A-2-4 Impact Compaction Results

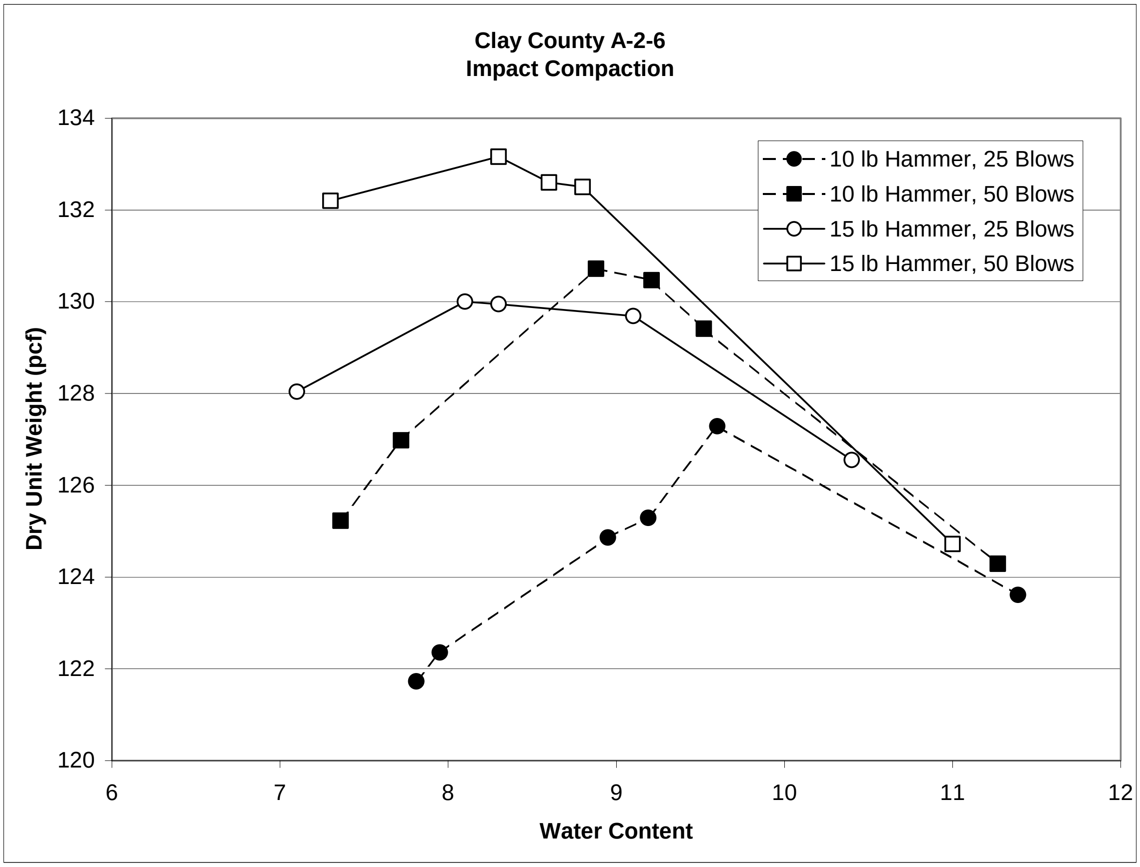


Figure 4.2 Clay County A-2-6 Impact Compaction Results

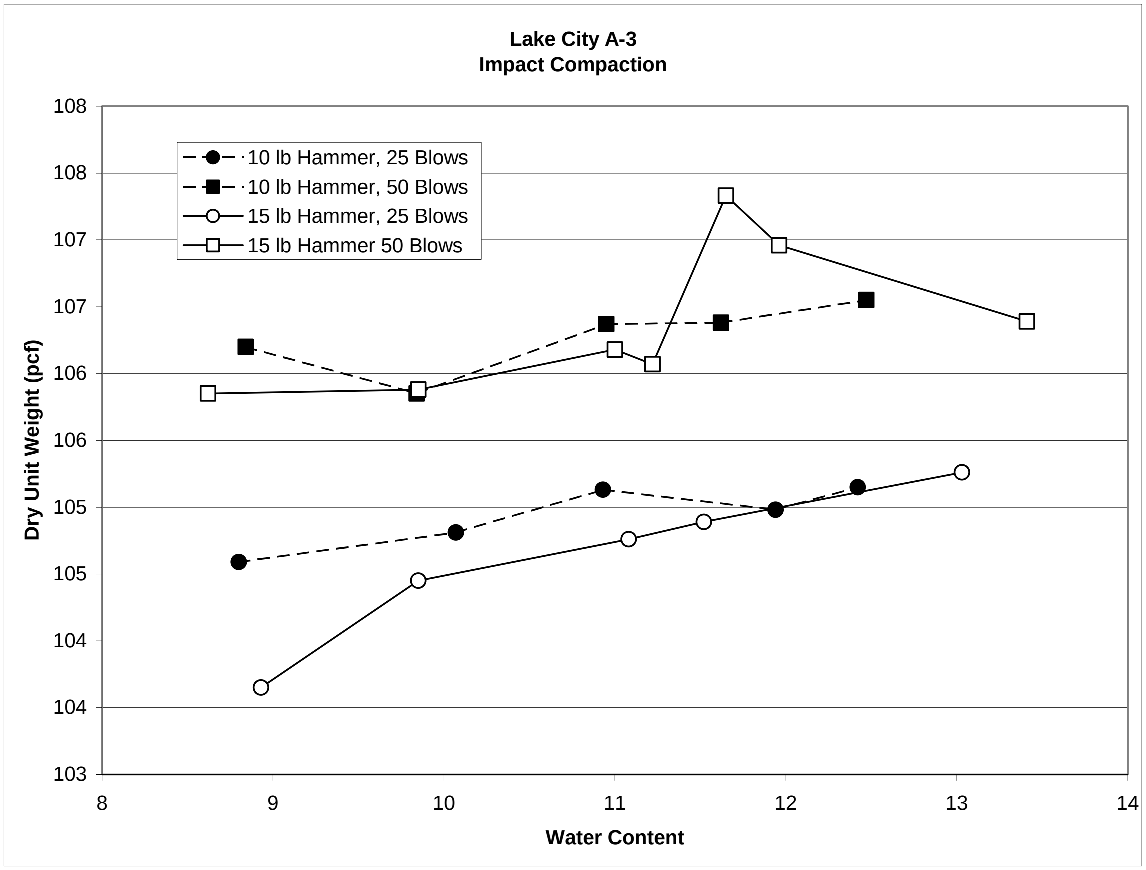


Figure 4.3 Lake City A-3 Impact Compaction Results

CHAPTER 5

FIELD STUDY OF COMPACTION CHARACTERISTICS

5.1 Introduction

The second major objective of this project was to conduct several field tests. The primary goal of these field tests was to develop field compaction curves that could be compared with compaction curves created in the laboratory. Through this comparison, determinations could be made on the effectiveness of current construction specifications. The field tests focused on construction sites utilizing sandy soils as embankment or stabilized subgrade materials. These test sites were selected for two reasons, first, sandy subgrades are very common in Florida and second, sandy soils were proven to be the most difficult to use with the current impact compaction standards.

5.2 Thomasville Road Field Test

The first field test was conducted on August 25, 1999. The test section was part of the reconstruction of Thomasville Road (U.S. 319) in Tallahassee, Florida

5.2.1 Preliminary Laboratory Investigation

Before the field test was conducted, samples of the stabilized subgrade were collected and tested in the laboratory to develop impact compaction curves at several energy levels. The soil was a sand with small percentages of fines (6% to 8%). The sand was classified as A-3 using the AASHTO classification system. The laboratory investigation of the soil began by producing a Modified Proctor compaction curve for the soil. After this, an additional compaction curve was created by increasing the number of hammer drops on each lift of soil from 25 to 50. Compaction curves were also developed at two other energy levels. These included a 15 lb hammer at 25 blows per lift, and a 15 lb hammer at 50 blows per lift. The compaction curves showed little effect from the increased hammer weight. This result was consistent with the A-3 soils that had been tested in the laboratory previously. As can be seen in Figure 5.1, the maximum dry density that was achieved in the laboratory was approximately 113 lbs/ft^3. Once the laboratory investigation had been completed the field test was conducted.

5.2.2 Thomasville Road Field Test Procedure

For the Thomasville Road field test, the stabilized subgrade was placed on five test strips, each approximately 300 feet long and 25 feet wide (see Figure 5.2). The test strips were compacted at increasing water contents, using an identical compaction pattern with two different compactors. The first was a Dynapac CA 251 padfoot vibratory roller. This compactor weighs approximately 25,000 pounds and features a 60 inch drum with four inch pads. The second compactor was a Caterpillar CS 563C smooth drum vibratory roller. It also weighed 25,000 pound and had a 61 inch drum. The first test section was mixed, to a depth of 12 inches, at the in-situ moisture content (approximately 7%). Once the subgrade was mixed, it was compacted using four passes of the sheepsfoot roller followed by four passes with the smooth drum roller. One pass is defined as both the forward and backward motion of the roller. This compaction pattern was the standard pattern being used by the contractor on the rest of the project site

.

After compaction, density was measured at three locations along the test strip. Density measurements were accomplished using a nuclear density guage at depths of six and 12 inches. In addition to the nuclear density tests, a speedy moisture test was conducted to determine the moisture content at each location. Once the density and moisture measurements were taken, the strip was compacted again using the same pattern. Density and moisture measurements were repeated following the second compaction.

After the completion of the first test strip, work moved to the second strip. The moisture content on the second test strip was raised, from the in-situ moisture, by running a water truck over the strip. Running the water truck over the strip one time resulted in an increase in moisture content of approximately two percent. The test strip was then mixed and compacted using the same technique as on the first, with density and moisture measurements taken in the same manner described earlier. This procedure was repeated on the five test strips with each strip receiving more water than the previous one.

5.2.3 Thomasville Road Field Test Results

The density and moisture data obtained during the field test was used to develop field compaction curves at two different energy levels. The energy levels correspond to the number of compactor passes applied to the test strips. The first energy level represents four passes each by the sheepsfoot roller and the flat drum roller. The second energy level reflects an additional four passes (eight total) by each of the compactors.

Although nuclear density measurements were taken at depths of 12 and six inches, the 12 inch measurements proved to be more consistent and therefore were used to analyze the field test results. The compaction curves for the two energy levels can be seen in Figure 5.3.

Figure 5.3 shows that an increase in compactive energy during the field test had little effect on the maximum dry density and the optimum moisture content of the subgrade soil. This effect is similar to that experienced during laboratory tests of the subgrade as well as the Lake City A-3 sand. In future field tests it may be necessary to start with a lower initial compactive effort, in order to better define the relationship between compactive energy and the maximum density and OMC. Figure 5.3 also shows that the maximum density achieved during the field test was approximately 114 lbs/ft^3. This density is much greater than the maximum density indicated by the modified Proctor test (111 lbs/ft^3) and is also higher than that achieved with the highest laboratory impact compaction energy (113 lbs/ft^3 with the 10 lbs Hammer-50 blows test procedure).

The optimum moisture content (OMC) for the field compaction was slightly less than that indicated by the highest impact compaction energy in the laboratory but significantly less than the OMC found from the Modified Proctor test. This suggests that there is a need to further modify the existing construction specifications. Specifications requiring higher densities may result in better long-term performance of roadways. As shown in this field test, it is possible for contractors to easily achieve densities that exceed the Modified Proctor maximum dry density.

5.3 Sun Coast Parkway Field Test

In February 2000, a second field test was conducted at the Sun Coast Parkway construction site, near Brooksville, Florida.

5.3.1 Sun Coast Parkway Field Test Procedure

The test procedure at the Sun Coast Parkway site was slightly different than that used at the Thomasville Road site due to the limitations of the test site area. The length of the test site would not allow for the test strips to be aligned adjacent to each other. To accommodate this limitation, test strips were constructed in lifts on top of each other. Three different adjacent areas were used to construct these lifts. The first three lifts were constructed in Area 1 (see Figure 5.5), Area 2 was the site of two lifts, and Area 3 was the site of the final lift. The six test lifts were approximately 200 feet long and 50 feet wide. The lifts were constructed in a manner such that the after compaction thickness was approximately 12 inches. The soil used during the field test was a yellow-brown sand with approximately three percent fines, classifying it as A-3 in the AASHTO classification system. The soil was compacted with an Ingersoll-Rand SD 100 smooth drum vibratory compactor. This compactor is very similar to the smooth-drummed vibratory roller that was used for the Thomasville Road field test (see Chapter 3). The compactor was operated at its highest vibratory frequency and at maximum speed, in accordance with the contractors usual operation.

The first test lift was compacted at the in-situ moisture content, approximately four percent. After six passes of the vibratory roller, density and moisture measurements were taken at two locations in the center of the test strip. Both the density and moisture measurements were conducted using a nuclear density gage at depths of six and 12 inches. After the measurements were completed the test strip was compacted with an additional four passes (10 total) of the compactor. Following the second compaction, the density and moisture content of the strip were retested. After the second set of measurements were taken, the second test lift was constructed on top of the first. Once the soil had been loosely placed, a water truck was used to raise the moisture content of the test strip. The second lift was then compacted in the same manner as the first, and density and moisture measurements were conducted after six and 10 passes. Using this same procedure, the third test lift was constructed on top of the second.

After the third test lift had been completed, the work moved to the second test area. Test Area 2 was the site of the next two test lifts. These lifts were put on embankment soil that had been placed previously by the contractor. The embankment soil had been compacted to the density required in the construction specifications and provided that same support to the test lifts as was experienced in Test Area 1. The fourth and fifth test lifts were completed using the same procedure as described above, with each test lift having a higher moisture content than the previous one. The final test lift was constructed in the Test Area 3, on top of previously compacted embankment material.

For the Sun Coast Parkway field test a compactive energy study was conducted simultaneously on the same test lifts by Ardaman & Associates, Inc. The test procedure and test results can be found in Ardaman & Associates, Inc (2001). A schematic plan and profile of this program for Test Site 1 are presented in Figure 5.6. As shown, one earth pressure cell was installed at the base of each lift, aligned with the approximate centerline of the roller track.

5.3.2 Sun Coast Parkway Field Test Results

As previously described for the Thomasville Road field test, the density and moisture measurements taken during both the Sun Coast Parkway field test and the Ardaman & Associates compactive energy test were used to develop field compaction curves. During the Thomasville Road field test, very little increase in density was achieved after eight passes of the compaction equipment. For this reason, results show that the compaction curves for the second field test would start at a lower compaction level. The first compaction curve for the Sun Coast Parkway field test represents a level of compaction equivalent to four to six passes of the field compactor. The second compaction curve used data points taken after 10 to 12 passes. The Sun Coast Parkway compaction data covers a wider range of moisture contents than the Thomasville Road compaction data. This helps in constructing more complete compaction curves. By using lower compaction energy levels than those used in the first field test, a better correlation was made between density and the number of roller passes in the field. Although nuclear density measurements were taken at depths of six and 12 inches, only the 12-inch measurements were used for the compaction curves. As was experienced during the Thomasville Road field test, nuclear density measurements taken at a depth of six inches proved to be inconsistent.

Due to the low fine content of the soil, it was difficult to keep the test strips at water contents above approximately eight percent during the field test. The free draining soil would not hold large amounts of water unless an excessive amount was applied. As a result, the moisture measurements during the field test tended to be on the low side of optimum. Even with this phenomenon, the contractor did not experience any difficulty bringing the soil to the required density. Once again showing that the current construction specifications for sandy soils are not representative of field conditions. In addition to the low moisture contents, several density measurements taken from the first test lift had to be disregarded. Several of the 12-inch density measurements taken from the first test lift were excessively high suggesting that the test depth was at or near the interface between the natural ground and the fill soil. The remaining data points were used to develop the compaction curves seen in Figure 5.7.

As can be seen in Figure 5.7, the maximum density on the four to six pass compaction curve is 107 lbs/ft^3 and the optimum moisture content is approximately seven percent. When the compactive energy was increased to 10 to 12 passes of the compactor, the maximum density increased to 110 lbs/ft^3. The highest density on the 10 to 12 pass curve occurred at a slightly lower moisture content than the maximum density on the four to six pass curve. This result is consistent with the hypothesis presented in the introduction of this report. The comparison of the field test results with the laboratory Proctor tests can be seen in Figure 5.8.

As can be seen in Figure 5.8, the maximum density for the Sun Coast Parkway soil obtained from the Modified Proctor laboratory compaction test was approximately 107 lbs/ft^3, at a moisture content of 13 percent. This maximum laboratory density is very similar to the maximum density obtained in the field after four to six passes of the compactor, but the field density was obtained at a much lower water content than that suggested by the Modified Proctor test. Much higher densities than those required by the current specifications (98 percent of the Modified Proctor density for stabilized subgrade) were achieved with only a few more passes of the compactor. For this field test, the maximum density after 10 to 12 passes of the compactor was 110 lbs/ft^3, whereas 98 percent of the Modified Proctor density is 104 lbs/ft^3. These results show that the current construction specifications drastically underestimate the maximum achievable field density for sandy soils. In addition to showing inaccuracies of the density requirements, these field test results also suggest that when dealing with sandy soils the moisture-density relationship in the field has little or no association with the moisture-density relationship suggested by the Proctor laboratory tests. Based on these moisture-density discrepancies, the conclusion has been made that impact compaction is not a reliable means of specifying density requirements for pure sands.

5.4 State Road 56 Field Test

The third and final field test was conducted on November 20th and 21st, 2000. The location of the field test was the State Road 56/I-75 interchange construction site near Land O'Lakes, Florida. As was the case with the Sun Coast Parkway field test, Ardaman & Associates, Inc. conducted a compactive energy study concurrently with the field test.

5.4.1 SR 56 Field Test Procedure

The field test was conducted in an area where the contractor was placing embankment material. The embankment material being used was a native soil that was being excavated on site and placed as roadway fill. The excavated soil was an A-3 loamy sand with approximately two percent fines. The soil was placed in test lifts that were approximately 300 feet long and 50 feet wide and to a depth of 12 inches after compaction. Due to the fact that the soil was excavated immediately prior to being placed on the test lifts, the initial moisture content of the soil was wet of optimum (approximately 13 to 14 percent). Soil for the first test lift was placed loosely at this high moisture content. The field equipment used to compact the test lifts was a Dynapac CA 251 smooth-drummed vibratory roller. This is the same model compactor used during the Thomasville Road field test, with the exception of the drum type.

Initial compaction of the first test lift was accomplished by making four passes with the compactor. One pass is considered the down and back travel of the roller. After the four passes had been completed, density and moisture measurements were taken at a central location in the test lift. The density measurement was conducted using a nuclear density gage at a depth of 12 inches and the moisture measurement was made with a speedy moisture gage. After the density and moisture were documented, an additional four passes (eight total) were made with the compactor. After the eighth pass, the density and moisture were again checked. At this point the density still failed to reach the required density for roadbed material, due to the high moisture content. The compactor continued to make passes on the test lift in order to bring the density up to the specification requirements. After making 20 passes with the compactor, the lift still failed to reach the required density and therefore could not be left in place. Because compacting the soil at such a high water content proved to be ineffective along with the desire to conduct test lifts at lower moisture contents, the first test lift was milled up and allowed to dry overnight. In addition to the first test lift, a second lift was placed loosely in an adjacent area so that the soil could dry overnight.

After drying, the moisture content of the soil from the first test lift dropped approximately three percentage points. The loose soil was smoothed out and compacted in the same manner previously described. The resulting lift was considered the second test lift. After four passes of the compactor were completed, density and moisture measurements were taken at several locations along the test lift, in order to provide a wider range of moisture contents. Several density and moisture measurements were also taken after eight passes had been completed. Reaching the required density proved to be much easier at the lower moisture content. The additional soil that was dried overnight was then placed on top of the completed second lift. This third test list was compacted using the same procedure as the rest with density and moisture measurements taken at several locations along the lift, after four and eight passes of the compactor. Due to the amount of time required to dry additional soil, the third lift was the final lift of the field test.

5.4.2 SR 56 Field Test Results

The density and moisture measurements taken during the State Road 56 field test were once again used to construct field compaction curves. One difference between the State Road 56 field compaction curves and the other field curves is that the moisture range is considerably smaller. Due to the fact that the in-situ moisture content of the field soil was above optimum, compaction data is only available over a small range. The compaction data corresponding to four and eight passes of the compactor can be seen in Figure 5.9.

The maximum modified Proctor density achieved using the State Road 56 field test soil was 113 lbs/ft^3 at a moisture content of 11 percent as shown in Figure 5.10. The field moisture content was generally near to, or slightly greater than, the modified Proctor optimum moisture content. Considering that the optimum moisture content decreases with increasing compactive energy, the optimum moisture content corresponding to the field compactive energy would generally be several percentage points lower than the modified Proctor optimum moisture content. With this in mind, establishing the field compaction curves using the available data would be difficult.

Although proper field compaction curves could not be established, comparisons of the peak densities achieved during the field test with those found using the Modified Proctor laboratory test are still usefull. The maximum density obtained from the Modified Proctor test is approximately 113 lbs/ft^3. This density is 0.5 lbs/ft^3 less than the peak density achieved after four passes of the field compactor and 1.0 lbs/ft^3 lower than the eight pass peak density. If current stabilized subgrade construction specifications were applied to this Modified Proctor result, the required density would be 110.4 lbs/ft^3, much lower than the densities obtained during the field test. Due to the small moisture range tested in the field, comparisons are difficult between the effect of moisture in the laboratory and the field. Though no clear conclusion can be made about the proper optimum moisture content for this soil, the field test results clearly show that densities greater than those required by current specifications can be achieved.

Table 5.1 Thomasville Road A-3 Laboratory Compaction Results

Water Content %	Dry Unit Weight, pcf				
	10 lb hammer 25 blows	10 lb hammer 50 blows	15 lb hammer 25 blows	15 lb hammer 50 blows	Vibratory Compaction
8.2	109.82				
9.1	109.43				
9.6	109.48				
10.6	110.51				
11.7	111.05				
12.2	110.67				
13.2	109.23				
13.5	108.93				
8.2		111.37			
9.1		111.88			
10.4		112.61			
11.2		112.95			
11.9		112.3			
9.2			109.69		
9.9			110.25		
10.1			110.71		
11.4			110.89		
12.8			109.04		
8.9				110.98	
10.4				112.53	
11				112.65	
11.4				112.67	
12.5				110.67	
8.03					107.76
10.09					109.66
11.95					109.51
12.62					105.5

Table 5.2 Thomasville Road Field Compaction Results

Water Content %	Dry Unit Weight at 12" Depth, pcf	
	8 passes	16 passes
7.0	111.6	
8.6	111.5	
10.6	111.3	
10.6	112.5	
10.8	113.8	
10.8	113.9	
11.9	111.5	
12.2	109.0	
12.9	106.7	
9.1		108.9
10.6		110.9
10.6		111.5
10.8		112.8
11.0		112.7
11.2		113.6
12.2		111.5
14.1		110.1

Table 5.3 Sun Coast Parkway Lab and Field Test Results

Water Content %	Dry Unit Weight, pcf				
	Lab Standard Proctor	Lab Modified Proctor	Field 4 to 6 passes	Field 10 to 12 passes	Vibratory Compaction (Laboratory)
11.0	103.6				
12.9	104.0				
14.6	104.5				
17.3	101.6				
9.0		105.5			
10.8		106.0			
13.1		106.2			
15.1		104.3			
5.0			106.6		
6.2			106.1		
6.8			105.3		
8.0			106.8		
10.9			103.5		
12.8			103.0		
4.4				108.6	
5.4				109.3	
5.7				110.1	
5.8				109.3	
7.0				110.0	
7.8				108.0	
9.4				107.7	
13.9				105.9	
15.8				104.9	
8.3					104.0
10.0					105.6
12.1					105.3
13.5					100.0

Table 5.4 State Road 56 Field Test and Lab Modified Proctor Test Results

Water Content %	Dry Unit Weight, pcf		
	Field 4 passes	Field 8 Passes	Modified Proctor
9.7	113.6		
10.3	112.1		
10.4	111.9		
10.6	112.8		
11.7	113.2		
11.7	111.7		
11.7	109.7		
12.8	106.4		
10.8		112.7	
11.9		114.1	
12.6		110.6	
13.5		107.6	
8.1			112.4
10.0			112.6
12.1			112.0
13.8			107.5

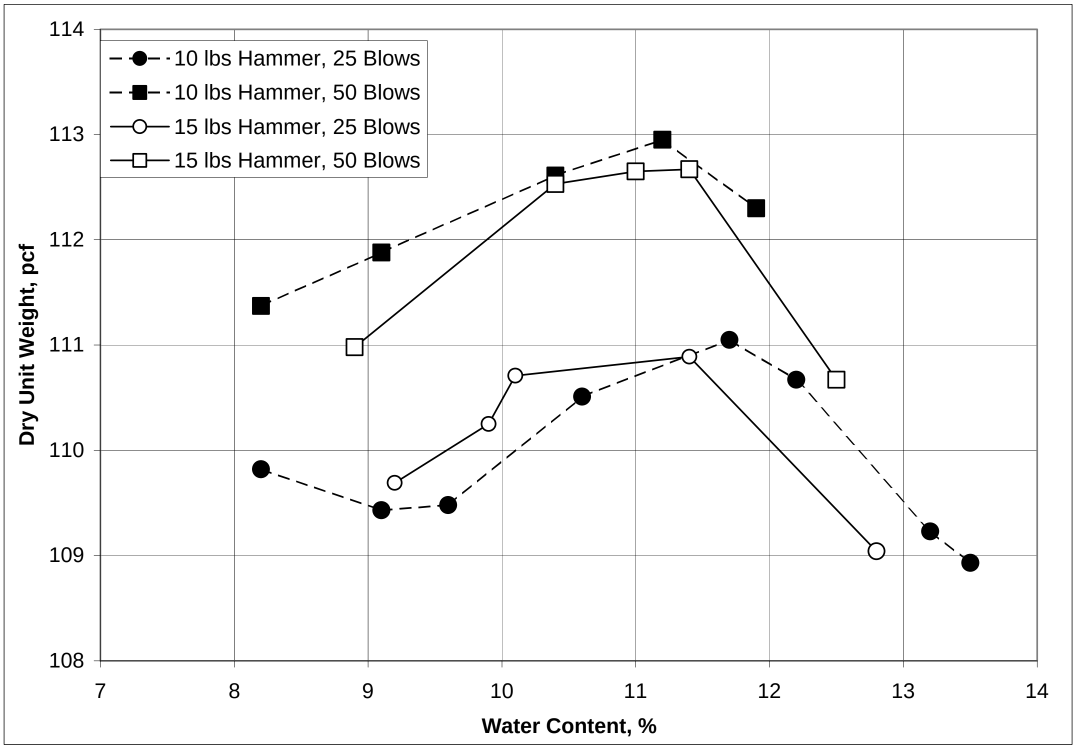
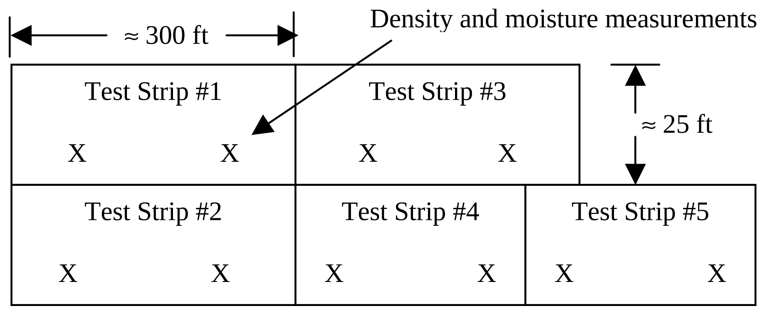


Figure 5.1 Thomasville Road A-3 Laboratory Impact Compaction



<u>Thomasville Road Field Test Layout</u>

Figure 5.2 Thomasville Road field test layout, density and moisture test.

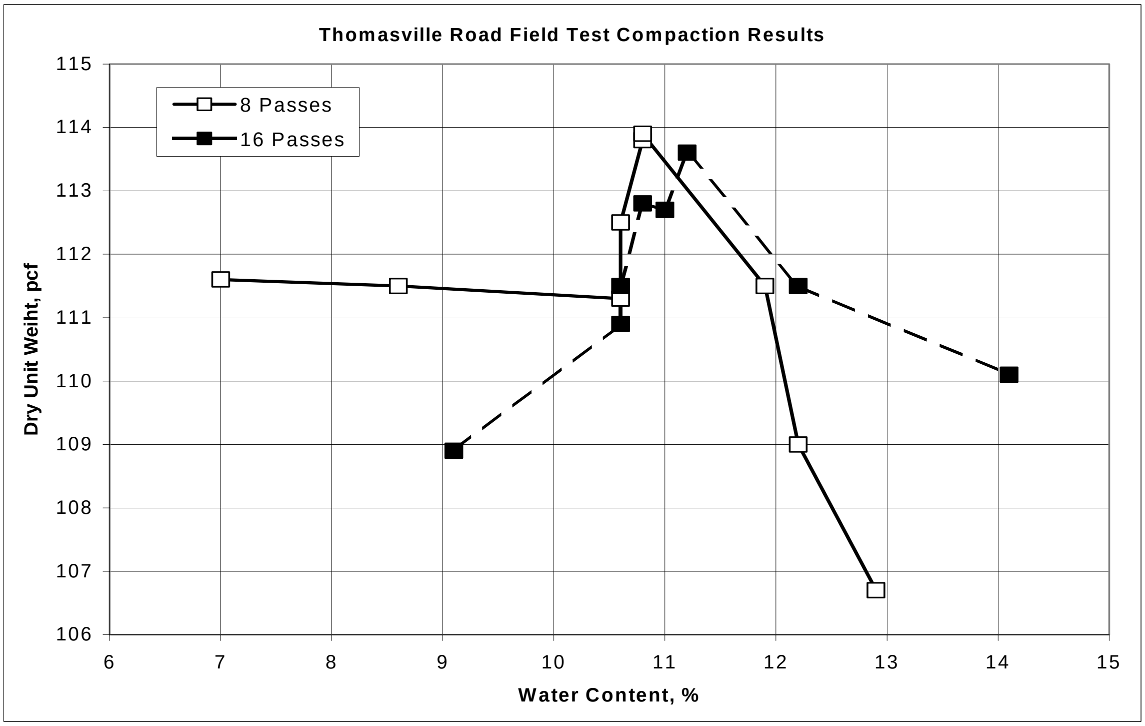


Figure 5.3 Thomasville Road Field Compaction Results

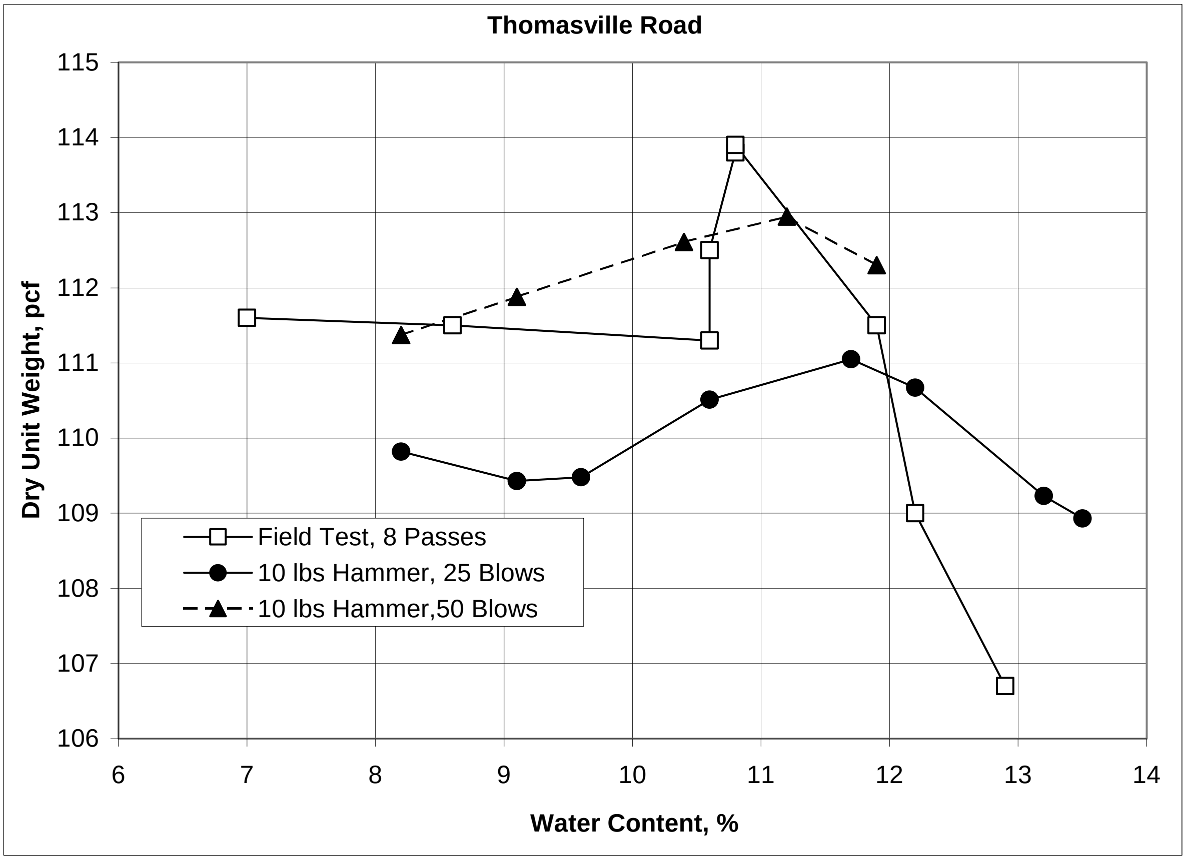


Figure 5.4 Thomasville Road Field Test vs. Laboratory Impact Compaction

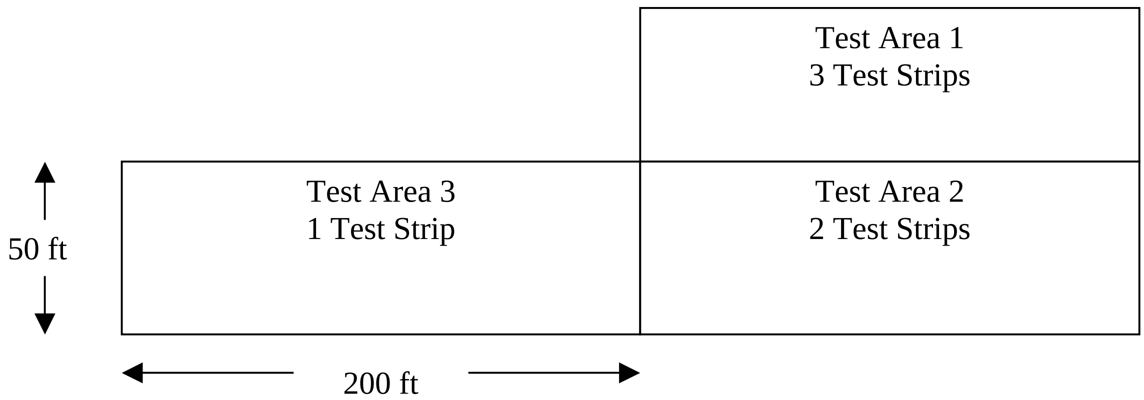
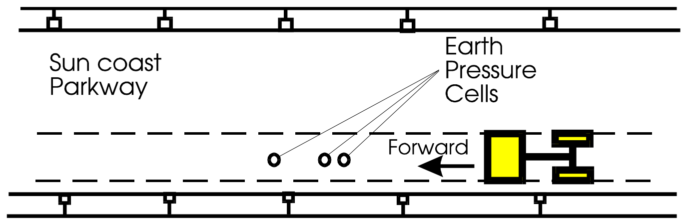
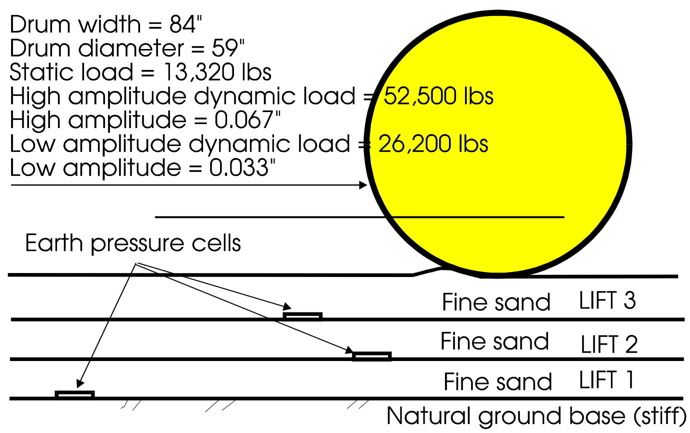


Figure 5.5 Sun Coast Parkway Field Test Layout



Schematic test site plan



Test site profile

Earth pressure cell

Figure 5.6 Sun Coast Parkway field test profile and earch pressure cell

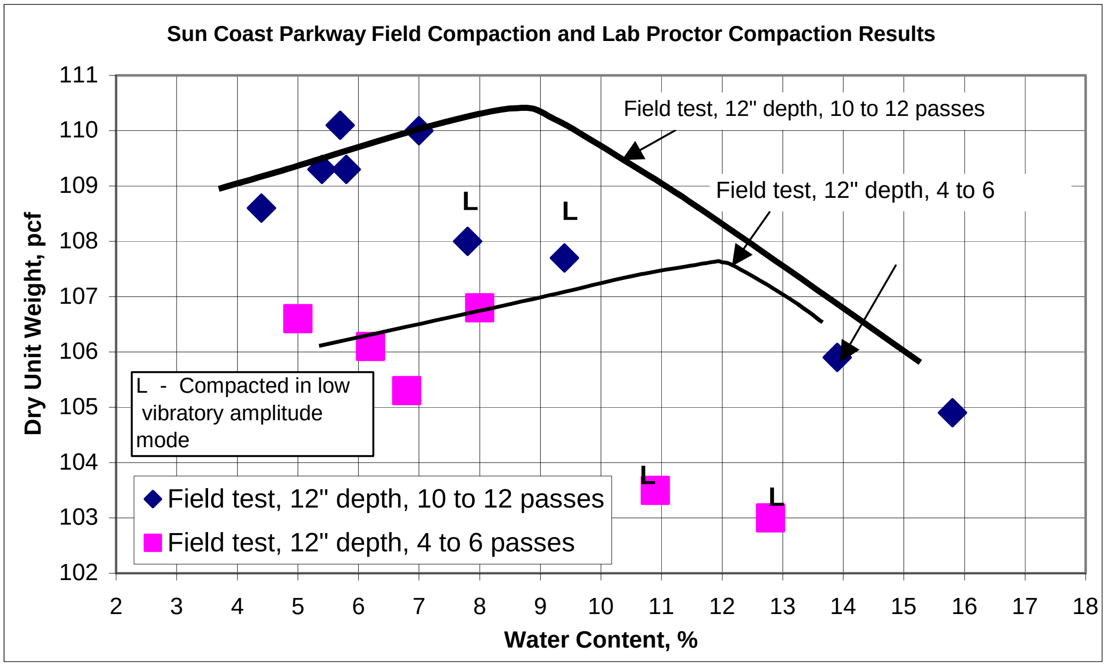


Figure 5.7 Sun Coast Parkway Field Test Results

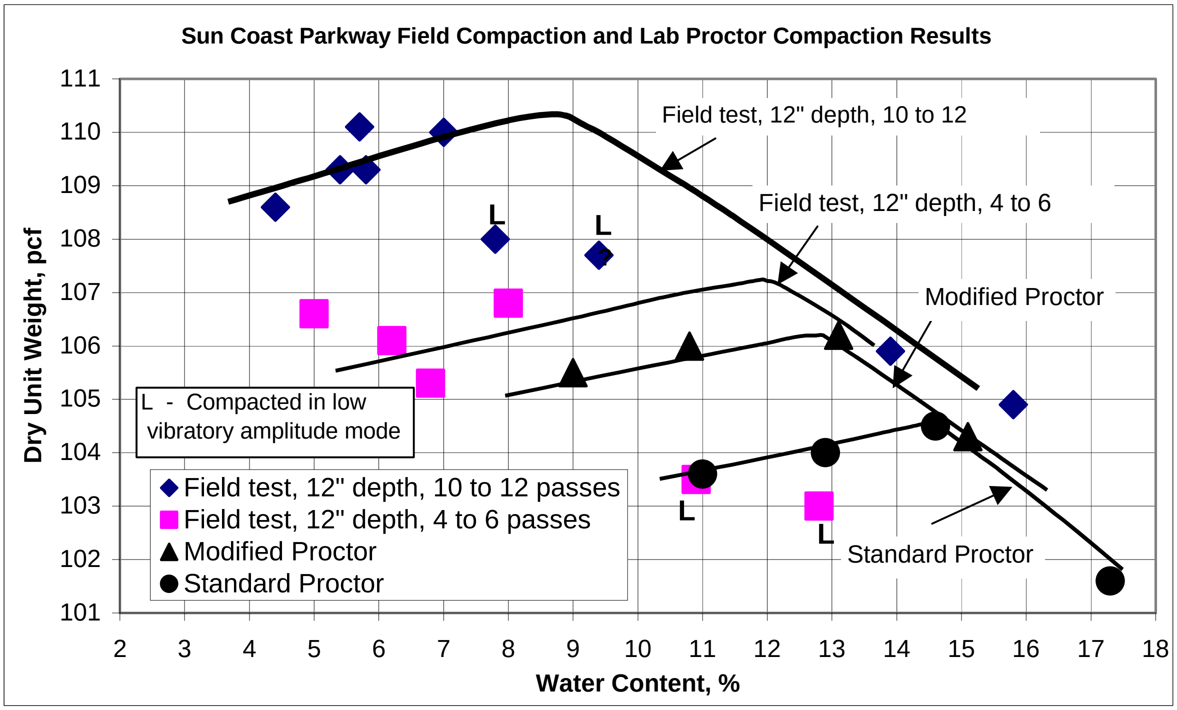


Figure 5.8 Sun Coast Parkway Field Test Results vs. Modified Proctor

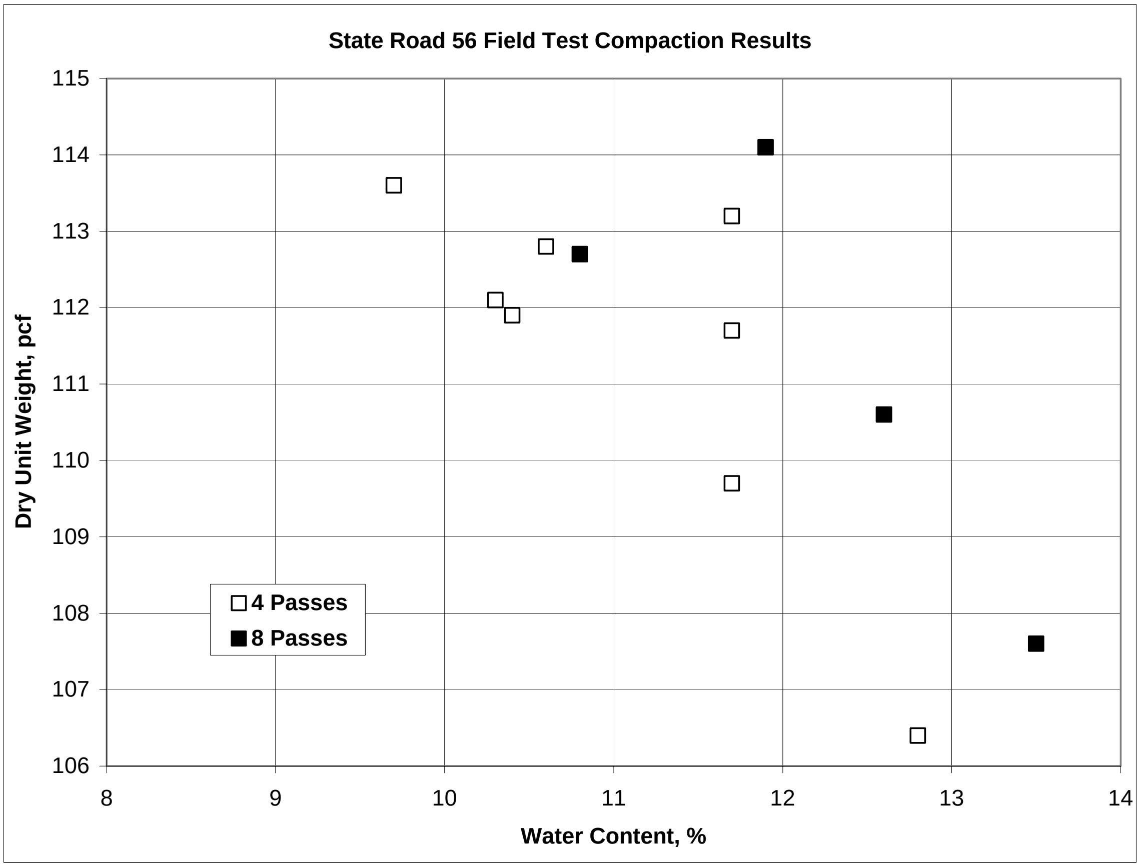


Figure 5.9 State Road 56 Field Test Results

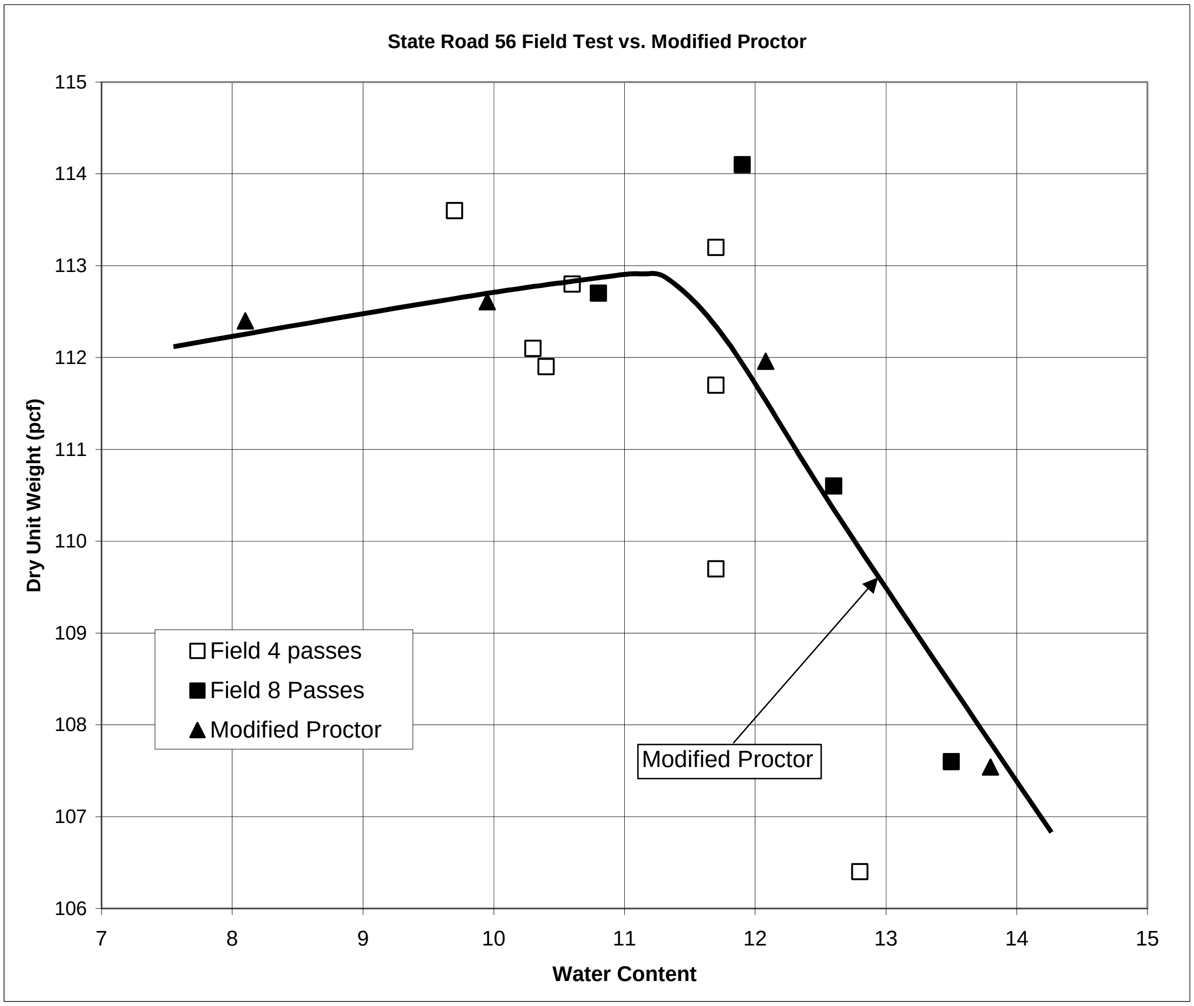


Figure 5.10 State Road 56 Field Test Results vs. Modified Proctor

CHAPTER 6

LABORATORY SIMULATION OF FIELD COMPACTION CHARACTERISTICS

6.1 Introduction

The results of the three field tests completed for this study showed significant discrepancies between field compaction conditions and the results obtained from the Proctor laboratory tests. Due to these discrepancies, using the Proctor laboratory tests to specify construction densities for A-3 soils is not an appropriate procedure. As mentioned previously, gyratory compaction is one laboratory compaction method that has shown considerable promise. History on the development of gyratory compaction equipment and testing procedures is provided in Chapter 2. Over the course of this study, an extensive testing program was completed in order to demonstrate the effectiveness of using gyratory compaction on granular soils. Currently, there are no published test procedures for compacting soils with a SuperPave gyratory compactor. To this point, the majority of research conducted on using gyratory compaction on soils has focused on replicating Proctor test results. Since the Proctor tests do not represent the maximum achievable field compaction for granular soils, gyratory test procedures should attempt to replicate field conditions and not the Proctor test results. The final stage of this compaction study was to develop a preliminary test procedure using gyratory compaction to replicate field compaction characteristics.

6.2 Gyratory Compaction Equipment

The gyratory compactor used during this investigation was the Industrial Process Controls Ltd. (IPC) Servopac Gyratory Compactor (Figure 6.1). The Servopac is a fully automated, servo-controlled gyratory compactor originally designed to compact asphalt mixes by means of the gyratory compaction technique. Compaction is achieved by simultaneous action of static compression and the shearing action resulting from the mold being gyrated through an angle about its longitudinal axis. The servo-control operation of the machine allows the vertical stress, gyratory angle, and gyration rate to be quickly modified from a hand-held pendant or personal computer (PC). An optional PC 'Windows' interface provides a screen to input test parameters and display and plot either height, density, or angle against gyratory cycles in real time. Test data may be stored and retrieved or transferred to other analysis packages. The Servopac is designed to comply with SHRP SuperPave asphalt mix design requirements. When compacting specimens using gyratory compaction, four factors influence test results. These factors are the gyration angle used, the vertical pressure applied, the rate of gyration, and the number of gyration cycles. The Servopac is capable of producing gyration angles between zero and three degrees, gyration rates up to 60 gyrations per minute, and vertical pressures as high as 600 kPa for as many as 999 gyration cycles.

6.3 Gyratory Testing Program

After the first two field tests (Thomasville Road and Sun Coast Parkway) were completed, preliminary work began on developing a gyratory compaction test procedure for replicating the field test results.

Previous research (Butcher, 1998) concluded that the gyration rate used to compact samples has very little effect on the test results. Therefore, the study conducted for this project concentrated on the influence of the gyration angle, vertical pressure, and number of gyration cycles used during laboratory compaction.

Due to the fact that there has been very little research on gyratory compaction of soils, a systematic approach was used to find an appropriate starting point. Since modern gyratory compactors were developed for compacting asphalt specimens, the SHRP SuperPave asphalt mix design procedure was initially used to determine appropriate gyration angle and vertical pressure ranges to be investigated. The SHRP procedure requires the use of a 1.25 degree gyration angle, and 600 kPa of vertical stress. A decision was made that optimal values for compacting soils most likely would not exceed the SHRP values because soils have much lower stiffness values as compared to asphalt samples and therefore require less energy to compact.

During the initial phases of the gyratory compaction investigation, numerous tests were complete in order to determine whether or not the gyratory compactor was capable of producing densities in the range of those experienced in the field. Once determined that gyratory compaction could successfully generate samples with these high densities, a comprehensive testing program was conducted on the field test soils. A decision was made that the test conditions include combinations of two different gyration angles (1.0 degree and 1.25 degrees), and varying vertical stresses varied from 100 kPa to 500 kPa. Each combination of these test variables would be used to compact samples for 30, 60, and 90 gyration cycles. All of the test procedures used a gyration rate of 20 gyrations per minute.

One issue that evolved during the testing program was the loss of water experienced by samples at high water contents. At lower compactive energies the water seepage was not severe, but as the test energy and most importantly the test duration was increased, water loss became a major problem in determining proper dry unit weights. The PC based software used to determine wet densities of samples after compaction, bases the wet density on the weight of the sample prior to compaction. If significant water loss is experienced during compaction, the post-compaction sample weight will be considerably less than the pre-test weight. Therefore, the wet density provided by the Servopac software may be inaccurate. If the wet density, based on the pre-test weight, is used in conjunction with the moisture content calculated after compaction, the resulting dry density will be higher than the actual density achieved during the test. This problem was experienced in samples with moisture contents wet of optimum. This phenomenon resulted in a compaction curve that did not peak but rather flattened out when the moisture content reached optimum. If the water loss was too excessive, the curve would not peak at all but rather continued to rise over the entire moisture content range.

To remedy this situation, tests conducted after the initial phase of the program did not use the wet density provided by the Servopac software. Instead, the height of the sample after compaction was obtained from the software, in order to calculate the after compaction volume of the sample. This volume was then used with the after compaction weight of the sample to calculate the appropriate wet density.

6.4 Gyratory Test Results

The test procedures described in the previous section were used to develop compaction curves for the soils from two field test sites, Thomasville Road and Sun Coast Parkway Road. The test results and curves are presented in Tables 6.1 & 6.2 and Figures 6.3-6.14. The results of these compaction tests were used to analyze the effect of each of the test variables

The number of gyration cycles for which a sample is compacted has a significant effect on the dry unit weight achieved. Figure 6.15 depicts this effect on both the Thomasville Road and Sun Coast Parkway soils. The dry unit weight of each sample increases with an increase in gyration cycles. However, with each incremental increase of gyration cycles (in this case 30 gyrations), the increase in dry unit weight becomes less. Eventually the increase in unit weight would become insignificant. While increasing the number of gyration cycles is a simple means of increasing compaction effort, difficulties arise when the test procedure is lengthened. Loss of water is the major impediment during the test. As the test procedure lengthens, more water is lost and it becomes difficult to obtain samples with post-compaction water contents higher than optimum.

As would be expected, an increase in the gyration angle also results in an increase in dry unit weight. However the increase in unit weight is minor when the gyration cycles are low and even less significant when the gyration cycles are increased. Also, the optimum moisture content decreases slightly as the gyration angle is increased. These effects are shown in Figure 6.16.

Figure 6.17 illustrates that increasing the vertical stress as a means of achieving a higher dry unit weight is not very effective when the vertical stress is higher than 200 kPa. This effect was similar to what was experienced in the laboratory during impact compaction tests of these same soils (Figure 5.1). During the impact compaction tests, increasing the hammer weight did not result in increased dry unit weights. Figure 6.17 shows that gyratory compaction was most effective on the Sun Coast Parkway soil when a vertical stress of 200 kPa (20 psi) was used. This vertical stress is within the range experienced during the field-stress monitoring program conducted by Ardaman & Associates, Inc. (Ardaman & Associates, 2001), where the peak stress values were in the range of 110 kPa and 420 Kpa (16 and 60 psi).

6.5 Evaluation of Field and Laboratory Compaction Results

The next phase of the investigation was to further examine the field and laboratory compaction test results for the two sandy soils. As shown in Figure 5.3, no significant difference exists between the field compaction curves of eight compaction passes and 16 compaction passes for the Thomasville Road soil. The Sun Coast Parkway compaction results are presented in Figure 6.18 (Ardaman & Associates, Inc. 2001), which shows that after eight passes the dry density remains relatively the same.

The field and laboratory compaction test results are summarized and presented in Figure 6.19. As shown in the figure, the maximum dry unit weight for the Sun Coast

Parkway soil obtained from the modified Proctor laboratory compaction test was approximately 106.5 pcf, at a moisture content of 13 percent. This dry density was very similar to the unit weights obtained in the field after four to six passes of the compactor, but the field unit weight was obtained at a much lower water content than the peak modified Proctor density (approximately five percent dry of the modified Proctor optimum moisture content). Much higher densities (unit weights) than those required by the current specifications (98 percent of the modified Proctor density for stabilized subgrade according to the Florida Department of Transportation construction specifications) were achieved with only a few more passes of the compactor. For this field test, the maximum dry unit weight after 10 to 12 passes of the compactor was 110 pcf, whereas 98 percent of the modified Proctor dry unit weight would be 104 pcf. These results showed that the current construction specifications drastically underestimate the maximum achievable field density for sandy soils.

The Thomasville Road test data in Figure 6.19 also indicates that the field dry densities obtained after eight passes of the compactor are much higher than those found using the modified Proctor laboratory procedure (114 pcf versus 111 pcf). These higher densities were also obtained at a moisture content approximately 1 ½ percentage points lower than the modified Proctor optimum moisture content. Based on the moisture-density discrepancies between the field and laboratory tests, the conclusion has been made that laboratory impact compaction is not a reasonable means of specifying density requirements for pure sands. As shown in this field test, contractors can easily achieve field densities that far exceeded the modified Proctor maximum dry unit weight.

The field compaction curves were then compared to laboratory gyratory compaction curves to ultimately determine if gyratory compaction is a viable method for compacting granular soils. As seen in Figure 6.19, the gyratory compaction curve falls close to the field test curves in terms of both maximum density and optimum moisture content. The gyratory test procedure with 200 kPa vertical pressure, 1.25 degree gyration angle, 90 gyrations, and 20 gyrations per minute showed considerable promise for replicating field compaction characteristics.

Table 6.1 Thomasville road gyratory compaction results

Revolution=90		Revolution=60		Revolution=30	
Water Content %	Dry Unit Weight pcf	Water Content %	Dry Unit Weight pcf	Water Content %	Dry Unit Weight pcf
Vertical Pressure=100 kPa, Angle=1.0					
8.64	110.02	8.64	108.73	8.64	106.16
10.63	110.37	10.63	109.07	10.63	106.48
10.92	112.74	10.92	111.64	10.92	109.32
11.79	112.90	11.79	111.79	11.79	109.91
12.49	112.45	12.49	111.61	12.49	110.05
Vertical Pressure=100 kPa, Angle=1.25					
7.84	109.17	7.84	108.05	7.84	105.77
9.10	111.29	9.10	110.07	9.10	107.62
9.40	111.33	9.40	110.48	9.40	108.92
11.40	113.23	11.40	112.16	11.40	110.45
11.66	110.16	11.66	109.12	11.66	107.24
Vertical Pressure = 200 kPa, Angle = 1.00					
6.28	107.72	6.28	106.53	6.28	104.22
9.03	109.15	9.03	107.92	9.03	105.48
9.54	111.19	9.54	109.75	9.54	107.08
10.98	113.12	10.98	111.72	10.98	108.98
11.30	112.26	11.30	111.25	11.30	108.67
Vertical Pressure=200 kPa, Angle = 1.25					
8.31	110.24	8.31	109.10	8.31	106.82
8.87	112.25	8.87	111.05	8.87	108.67
9.54	113.09	9.54	111.95	9.54	109.88
10.89	113.28	10.89	112.36	10.89	110.70
11.12	111.57	11.12	110.43	11.12	108.51
Vertical Pressure = 300 kPa, Angle=1.25					
		8.30	110.53		
		9.00	112.03		
		10.20	112.40		
		10.98	113.23		
		12.33	111.06		

Table 6.2 Sun Coast Parkway gyratory compaction results

Revolution=90		Revolution=60		Revolution=30	
water Content %	Dry Unit Weight pcf	water Content %	Dry Unit Weight pcf	water Content %	Dry Unit Weight pcf
Vertical Pressure=100 kPa, angle =1.00 degree, rate = 20 gyration/minute					
8.37	105.21	8.37	104.17	8.37	102.01
9.35	105.25	9.35	104.23	9.35	102.04
10.50	105.33	10.50	104.27	10.50	102.12
10.70	105.88	10.70	104.88	10.70	102.69
11.10	107.59	11.10	106.58	11.10	104.60
11.80	107.12	11.80	106.11	11.80	104.27
Vertical Pressure=100 kPa, angle =1.25 degree, rate = 20 gyration/minute					
8.65	106.05	8.65	105.13	8.65	103.17
10.18	106.45	10.18	105.49	10.18	103.51
11.20	107.96	11.20	107.09	11.20	105.13
11.75	107.84	11.75	106.66	11.75	105.21
14.30	105.40	14.30	104.50	14.30	102.78
Vertical Pressure=200 kPa, angle =1.00 degree, rate = 20 gyration/minute					
7.68	106.77	7.68	105.74	7.68	103.68
10.57	107.27	10.57	106.23	10.57	104.16
11.02	107.30	11.02	106.30	11.02	104.22
11.78	106.93	11.78	105.99	11.78	104.24
Vertical Pressure=200 kPa, angle =1.25 degree, rate = 20 gyration/minute					
8.48	106.97	8.48	106.03	8.48	104.25
10.00	108.77	10.00	107.87	10.00	106.00
10.90	109.65	10.90	108.74	10.90	106.97
11.20	108.83	11.20	107.89	11.20	106.38
11.70	108.11	11.70	107.47	11.70	105.74
Vertical Pressure=300 kPa, angle =1.25 degree, rate = 20 gyration/minute					
		7.76	106.98		
		9.64	107.15		
		10.70	107.44		
		11.79	107.08		
Vertical Pressure=400 kPa, angle =1.25 degree, rate = 20 gyration/minute					
		7.68	106.85		
		10.01	107.16		
		10.51	108.42		
		10.90	107.85		
Vertical Pressure=500 kPa, angle =1.25 degree, rate = 20 gyration/minute					
		7.62	106.47		
		10.17	107.47		
		10.67	107.59		
		11.00	107.58		
		11.07	107.36		

Figure 6.1 Servopac Gyratory Compactor.

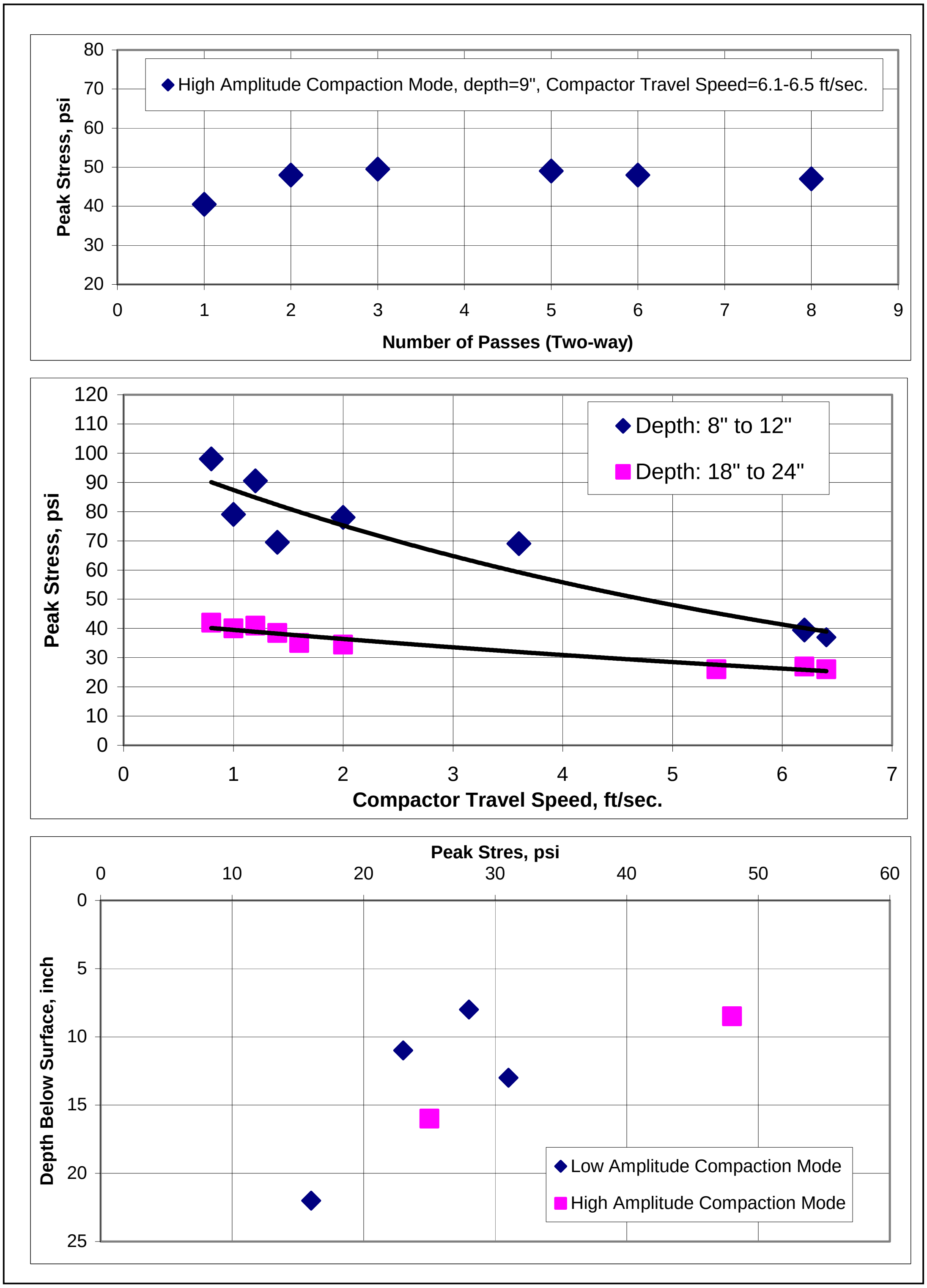


Figure 6.2 Measured peak stress amplitude versus number of passes, compactor travel speed, and depth below surface.

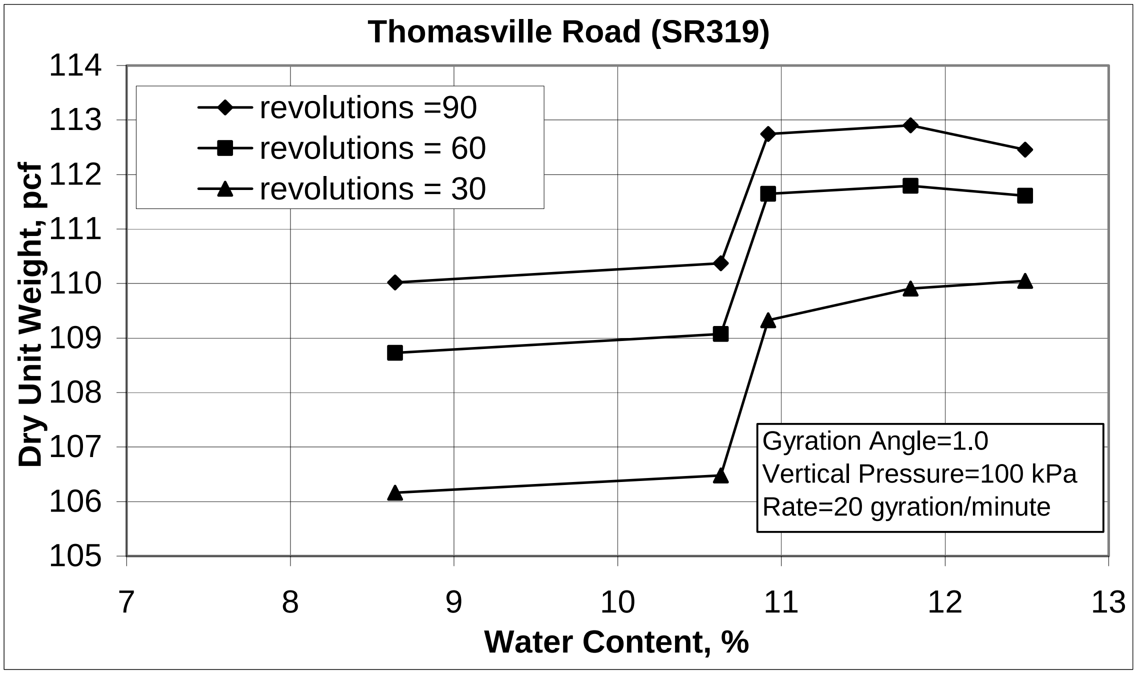


Figure 6.3 Compaction curves at 1.0 degree gyration angle, 100 kPa vertical pressure, and different gyrations for Thomasville road soil.

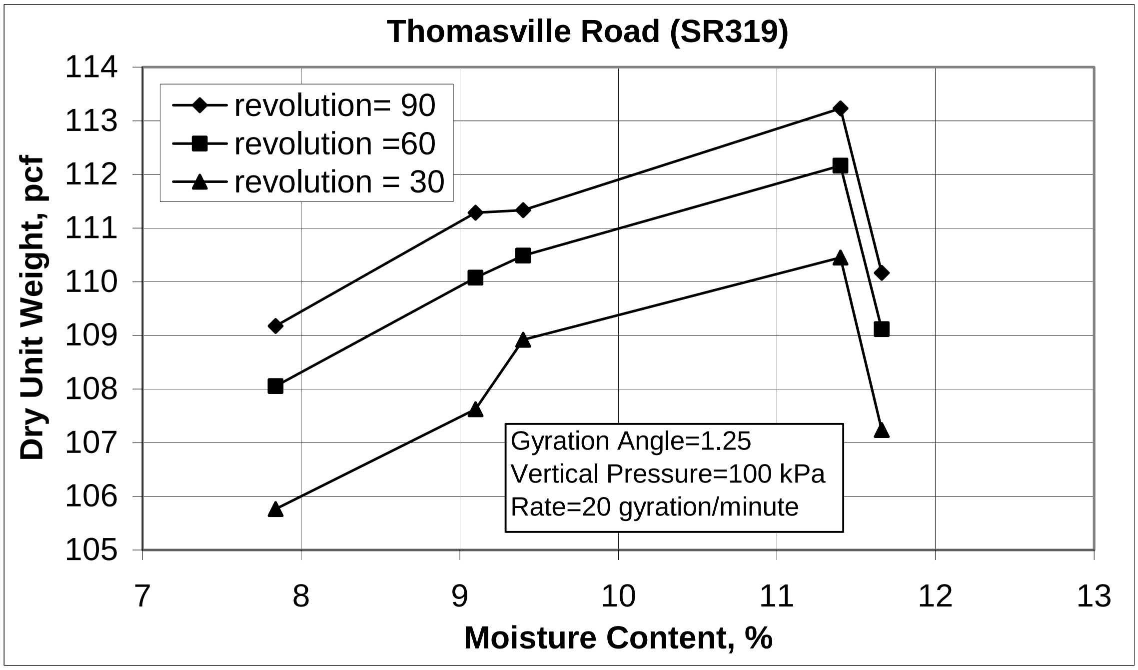


Figure 6.4 Compaction curves at 1.25 degree gyration angle, 100 kPa vertical pressure, and different gyrations for Thomasville road soil.

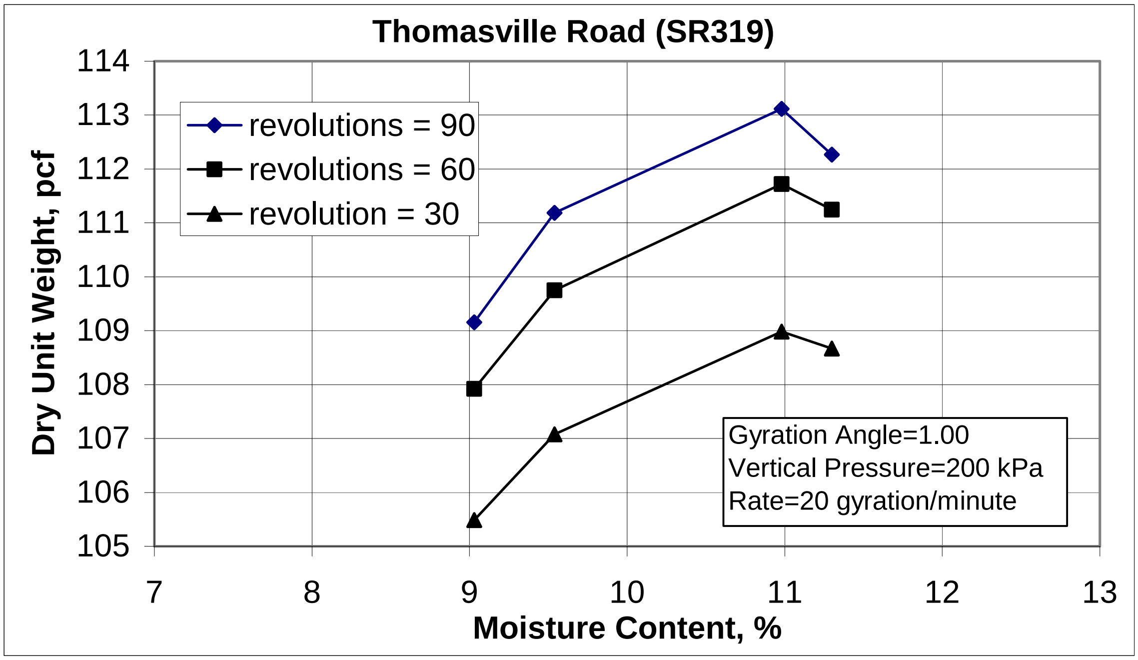


Figure 6.5 Compaction curves at 1.0 degree gyration angle, 200 kPa vertical pressure, and different gyrations for Thomasville road soil.

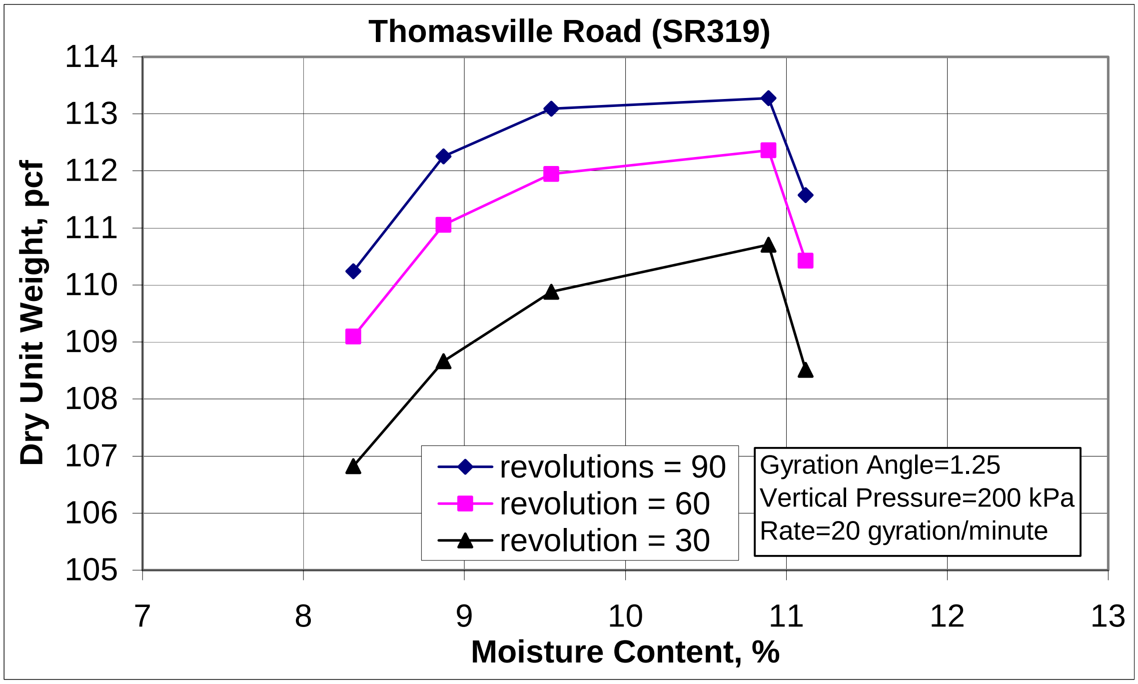


Figure 6.6 Compaction curves at 1.25 degree gyration angle, 200 kPa vertical pressure, and different gyrations for Thomasville road soil.

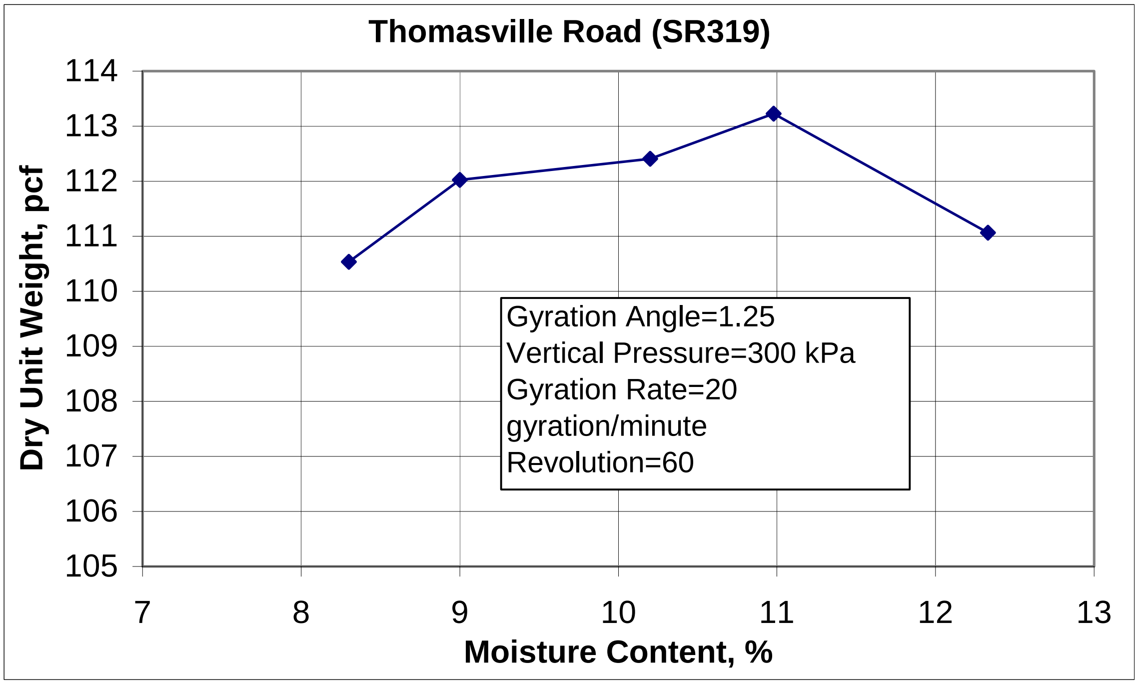


Figure 6.7 Compaction curves at 1.25 degree gyration angle, 300 kPa vertical pressure, and 60 gyrations for Thomasville road soil.

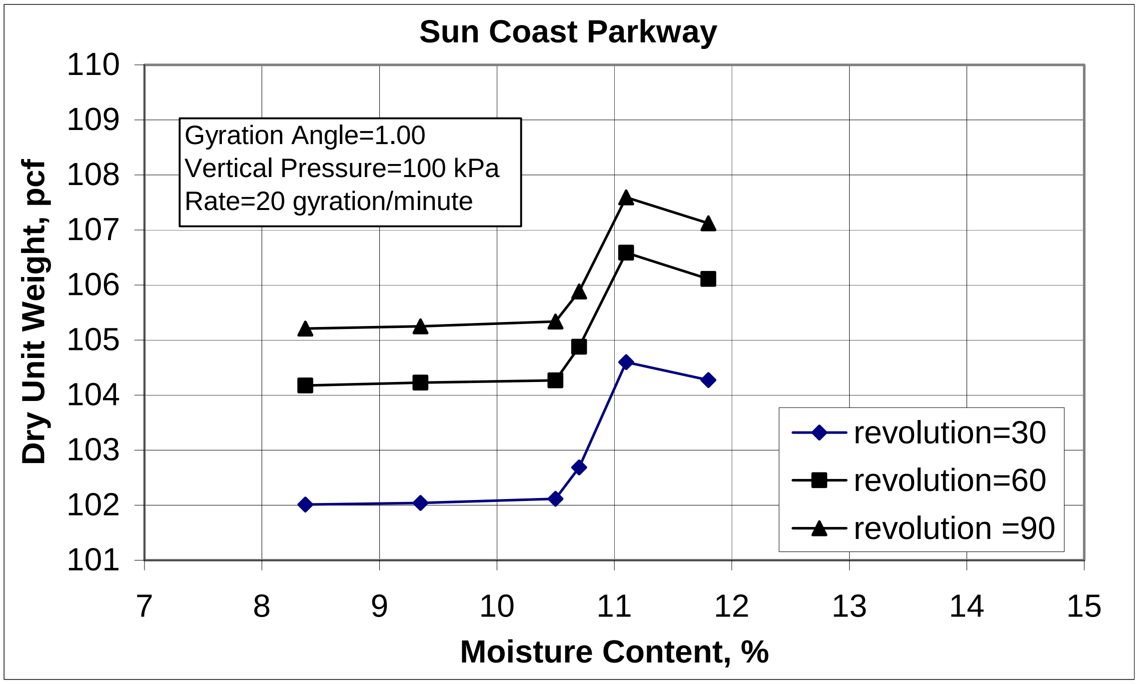


Figure 6.8 Compaction curves at 1.0 degree gyration angle, 100 kPa vertical pressure, and different gyrations for Sun Coast Parkway soil.

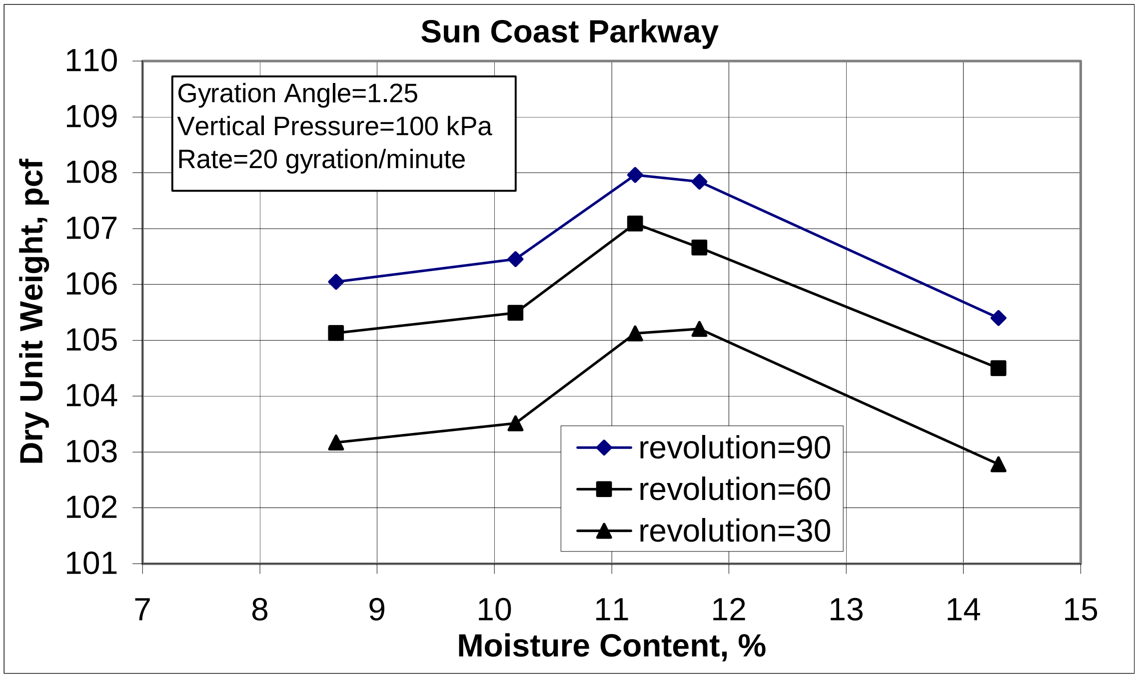


Figure 6.9 Compaction curves at 1.25 degree gyration angle, 100 kPa vertical pressure, and different gyrations for Sun Coast Parkway soil.

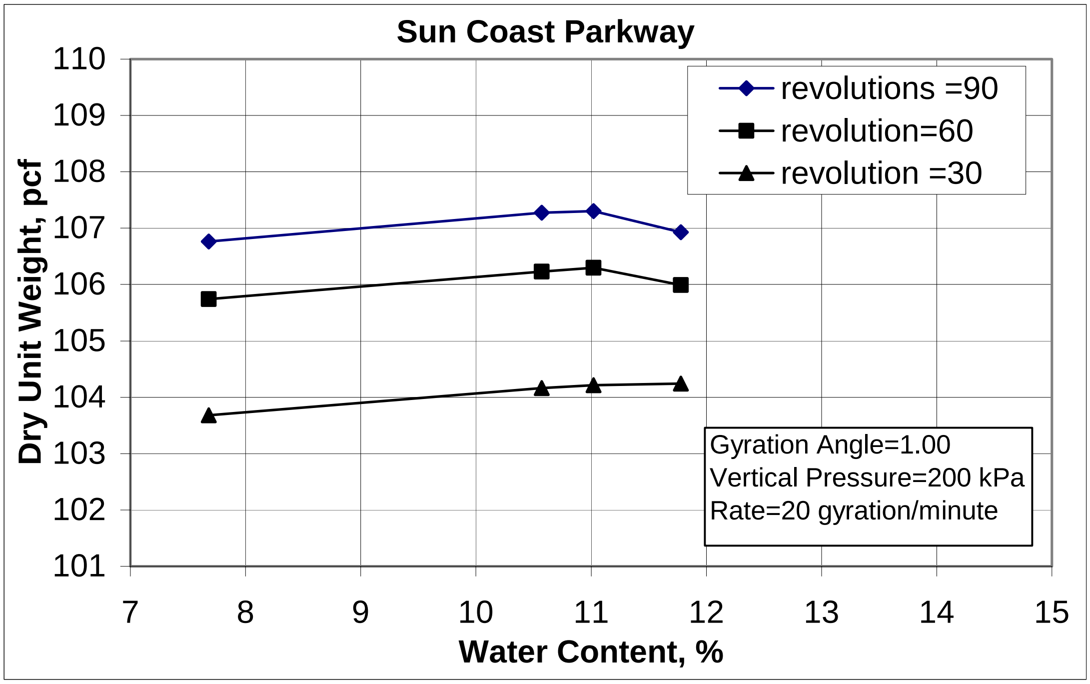


Figure 6.10 Compaction curves at 1.00 degree gyration angle, 200 kPa vertical pressure, and different gyrations for Sun Coast Parkway soil.

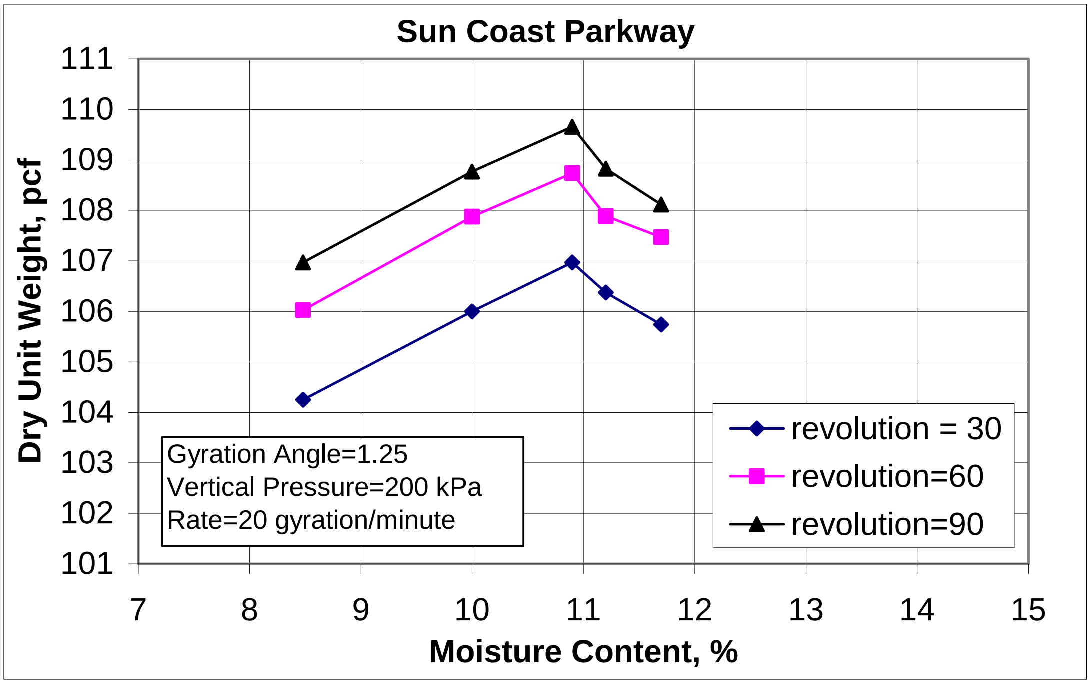


Figure 6.11 Compaction curves at 1.25 degree gyration angle, 200 kPa vertical pressure, and different gyrations for Sun Coast Parkway soil.

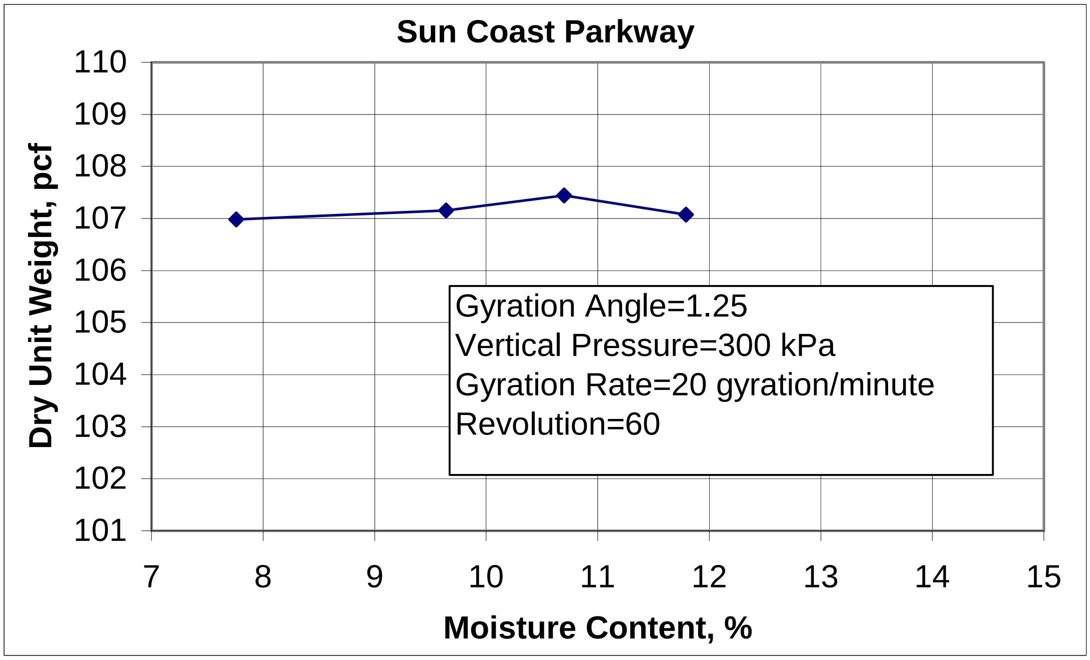


Figure 6.12 Compaction curves at 1.25 degree gyration angle, 300 kPa vertical pressure, and 60 gyrations for Sun Coast Parkway soil.

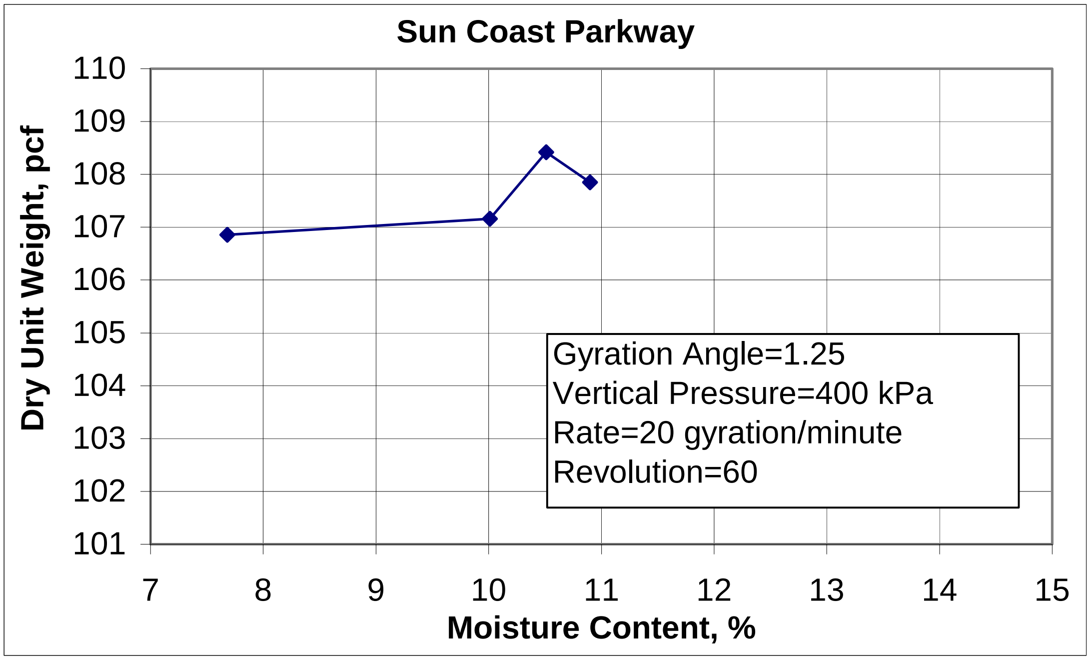


Figure 6.13 Compaction curves at 1.25 degree gyration angle, 400 kPa vertical pressure, and 60 gyrations for Sun Coast Parkway soil.

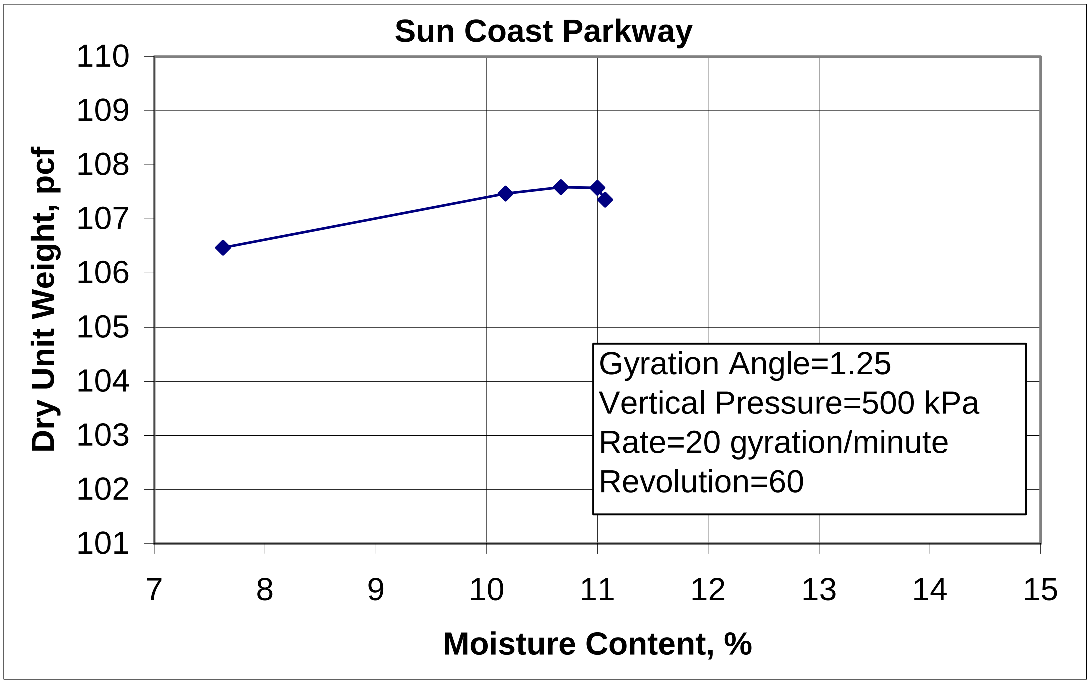


Figure 6.14 Compaction curves at 1.25 degree gyration angle, 500 kPa vertical pressure, and 60 gyrations for Sun Coast Parkway soil.

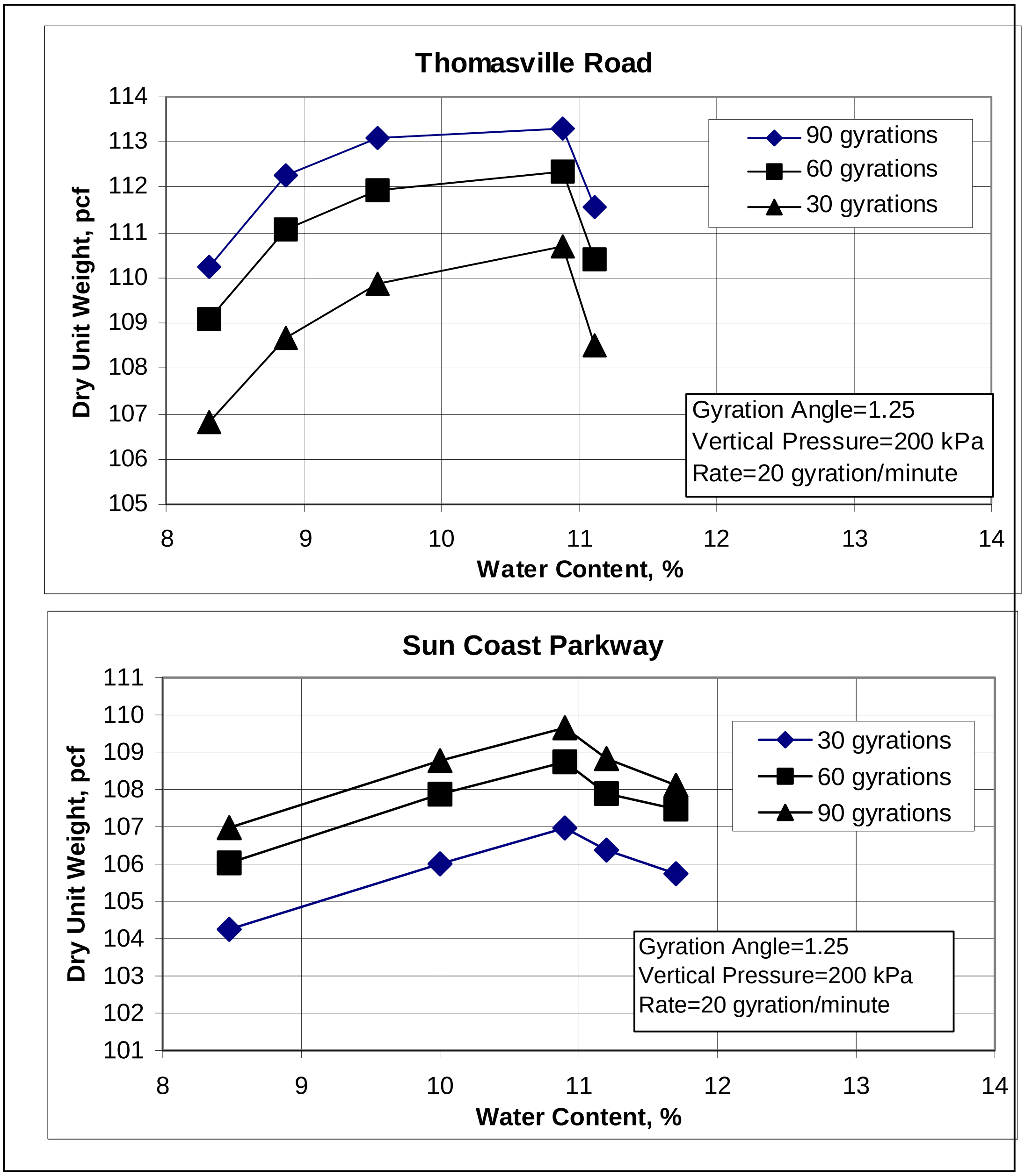


Figure 6.15 Effect of gyration cycles on dry unit weight.

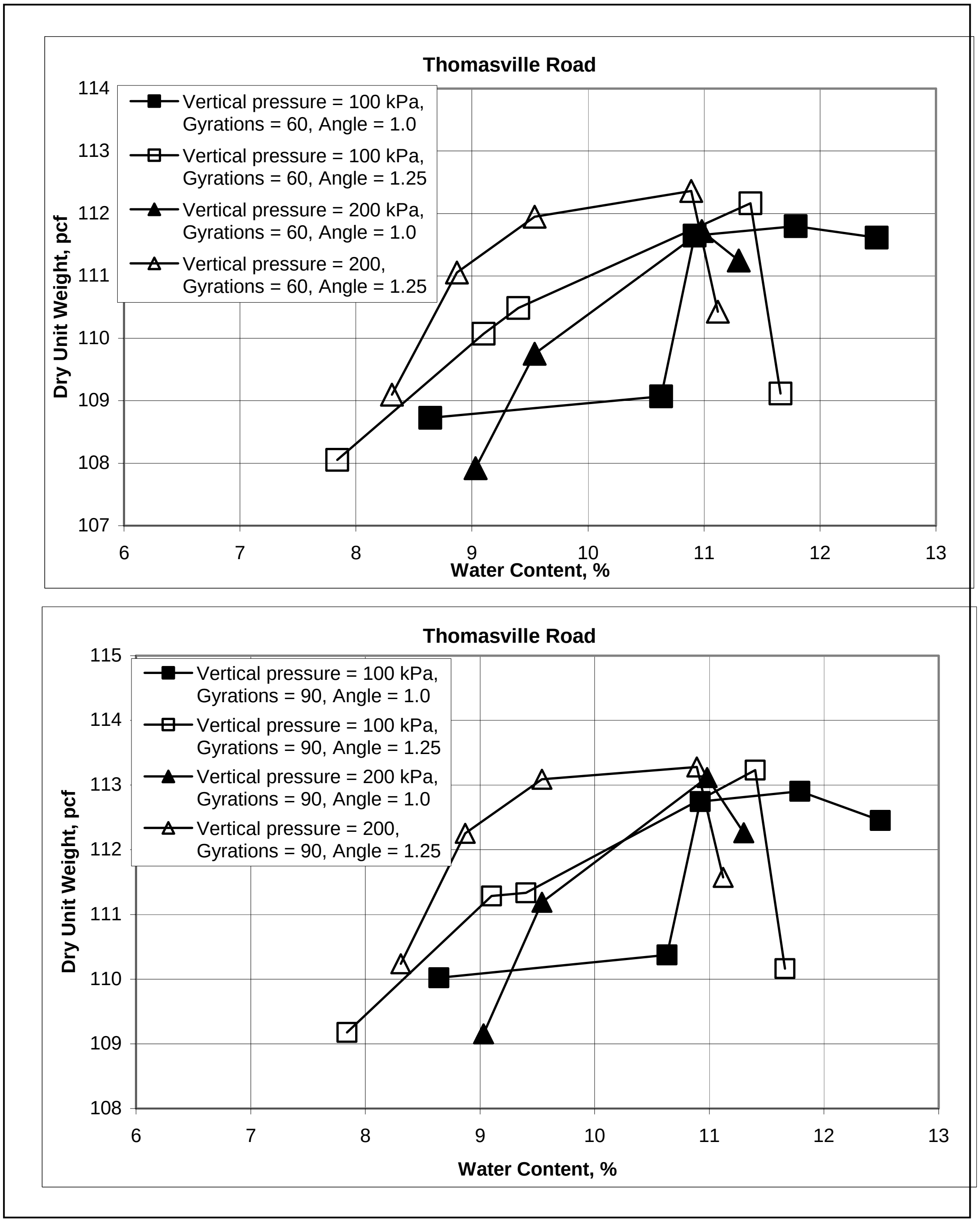


Figure 6.16 Effect of gyration angle on dry unit weight.

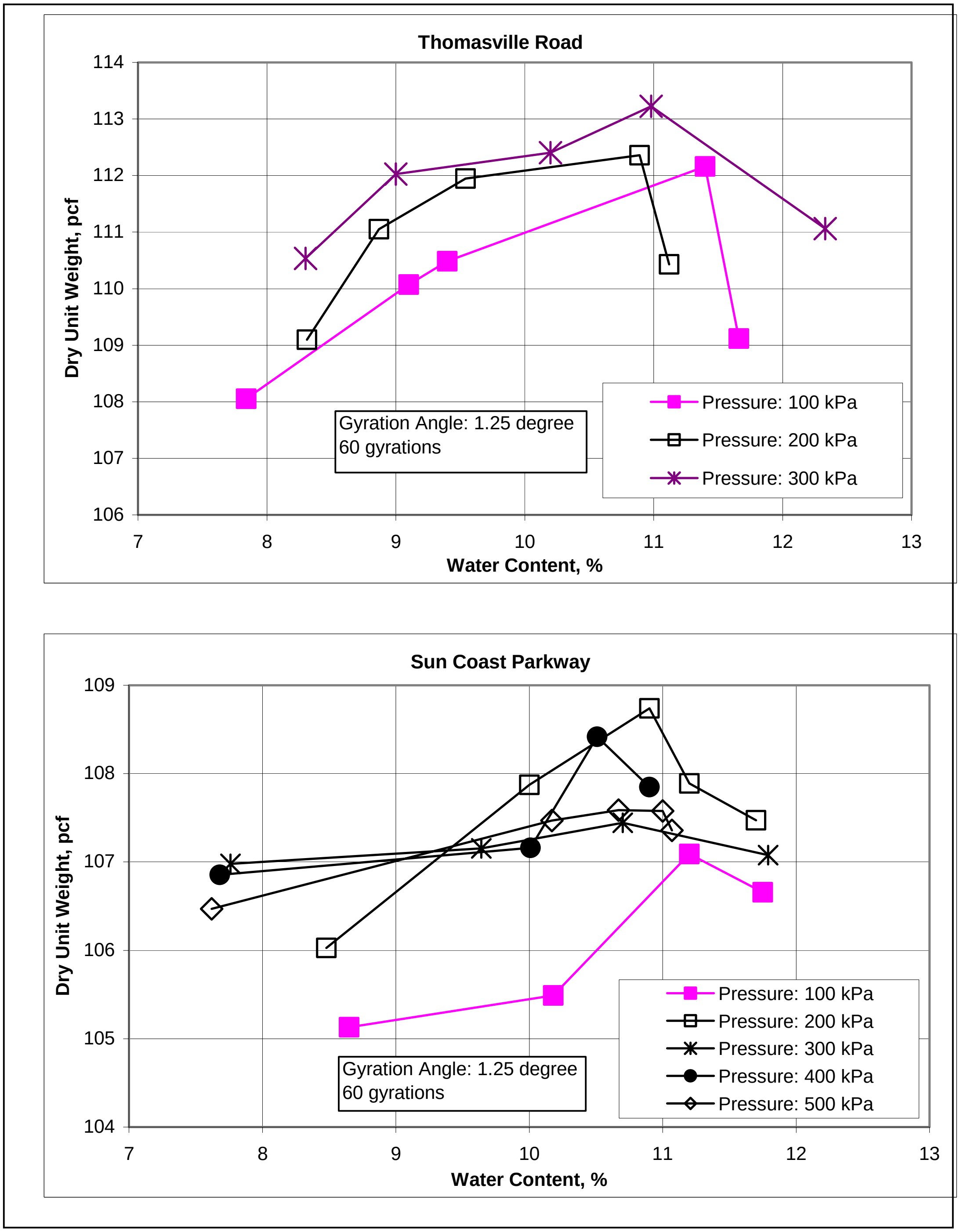


Figure 6.17 Effect of vertical pressure on dry unit weight.

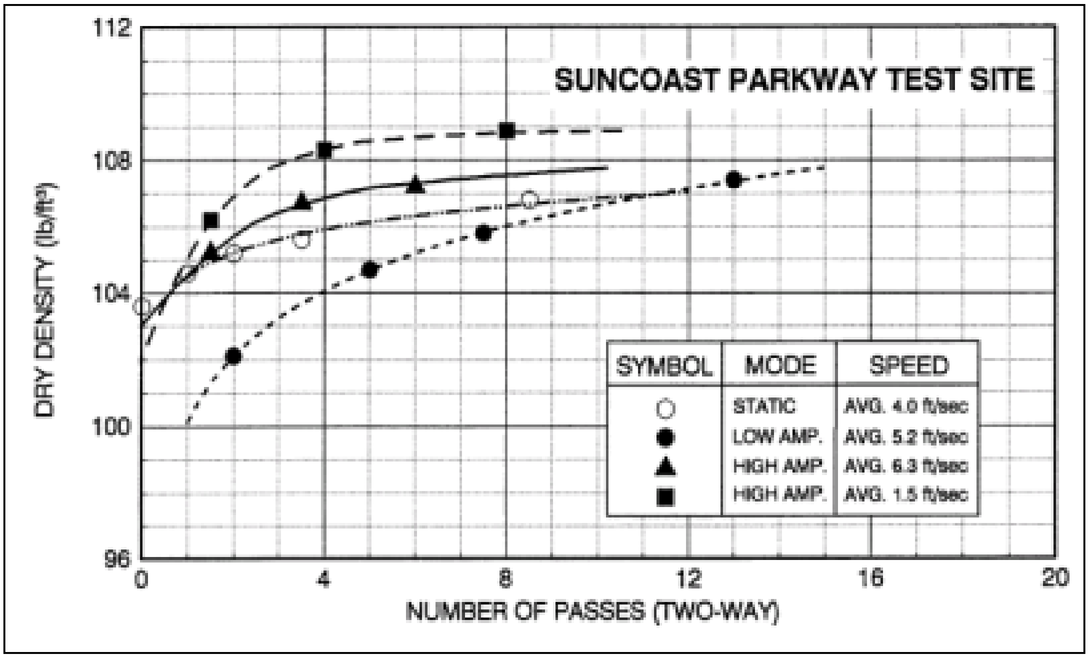


Figure 6.18 Dry unit weight versus number of passes at Sun Coast Parkway field test.

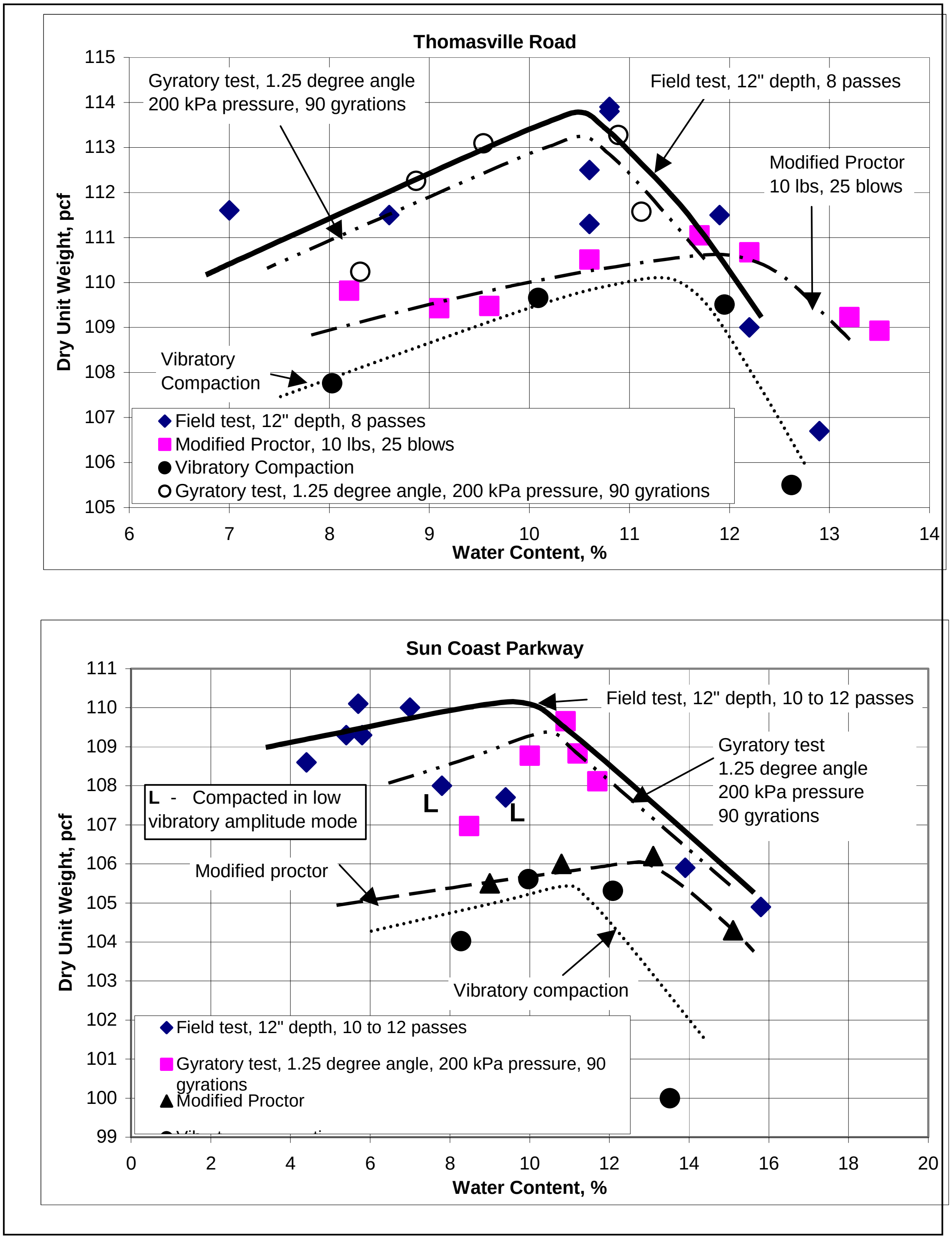


Figure 6.19 Comparison of field and laboratory test results.

CHAPTER 7

CONCLUSIONS

The conclusions based on the analysis and findings of this experimental study are summarized below.

1. Numerous tests have shown that impact compaction is not an adequate procedure for compacting pure sands in the laboratory. The standard and modified Proctor test procedures, AASHTO T90 and T180, respectively, were not developed for use with cohesionless soils.
2. Three field tests had shown that with the advent of advanced earthmoving and compaction field equipment, the AASHTO T90 and T180 test procedures no longer represented the maximum achievable field dry unit weights for A-3 sands. Dry unit weights substantially greater than the modified AASHTO maximum dry density were achieved in the field with a reasonable number of passes when using conventional vibratory compaction equipment on sandy soils when the in-place moisture content was less than or equal to the optimum moisture content corresponding to the field compactive effort.
3. The optimum moisture content corresponding to the field compactive effort was likely less than the modified AASHTO optimum moisture content when sand fill was compacted by more than three passes of a conventional vibratory compactor.
4. For the gyratory compact test, using the vertical stress as a means of increasing the dry unit weight was not effective when the vertical stress is more than 200

kPa. The 200 kPa stress level is within the range of peak vertical stresses measured during the field tests.

5. In the field, compaction after eight passes of conventional vibratory compaction equipment has little effect on the dry unit weight.

6. Gyratory compaction was more reliable than impact compaction when compacting pure sands in the laboratory. The gyratory test procedure with 200 kPa vertical pressure, 1.25 degree gyration angle, 90 gyrations, and 20 gyrations per minute showed considerable promise for replicating field compaction characteristics.

7. Further investigation needs to be completed in order to develop a standardized test procedure for compacting sandy soils with gyratory compaction.

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