FEASABILITY OF USING A GYRATORY COMPACTOR TO DETERMINE COMPACTION CHARACTERISTICS OF SOIL

by

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ABSTRACT

Proctor impact compaction tests represent the most commonly used laboratory method to determine the maximum dry unit weight and optimum moisture content of soils in the United States. Soil compaction methods in the field have changed dramatically over the last 50 years, though the Proctor tests have remained relatively unchanged. One shortcoming of the Proctor tests is that it uses impact loads to compact the soil in a stiff non-yielding mold. This technique may not accurately simulate modern field compaction methods, which rely on a combination of kneading, vibration, and increased normal pressures to achieve high dry unit weights. Consequently, a more appropriate method of compacting soils in the laboratory is needed. The research presented herein explores the feasibility of using a Superpave Gyratory Compactor (SGC) to compact soil specimens. The SGC was created in the early 1990s to accurately represent in-place asphalt densities. Gyratory compactors simultaneously use static compression and a shearing/kneading action to compact asphalt mixtures.

Variables within gyratory compaction (confinement pressure, number of gyrations, soil type, and moisture content) were explored to determine their effects on soil compaction. Gyratory compaction results, expressed in terms of dry unit weight and optimum moisture content, were compared to traditional laboratory compaction methods (Proctor and relative density tests). These results indicated that each soil type (A-1-a, A-3, A-4, and A-7-6) was sensitive to one or more of the gyratory compaction variables.

When compacted with moisture soil dry unit weights obtained from gyratory compaction surpassed the dry unit weights of traditional compaction methods for the majority of soils tested; therefore, gyratory compaction was considered a feasible and effective method of laboratory soil compaction. A-4 was the only soil whose dry density did not surpass some of traditional compaction tests.

Continued research is needed to develop a standardized protocol for gyratory compaction of soils as well as gain a more thorough understanding of free-draining soil. Future studies may also gain a better understanding of gyratory compaction by comparing dry unit weights, pressures, or energies of gyratory compaction to field compaction instead of existing laboratory compaction techniques.

CHAPTER 1

INTRODUCTION

Background

Soil compaction has been used by engineers and builders for centuries as a method of building bigger, stronger structures. Often the engineering properties of fills and native soils are less than desirable; therefore, soil compaction is performed to enhance these properties. In today's modern world, soil compaction is vital for applications such as roadways, dams, and embankments were the soil is the primary engineering material for construction. Following are some of the benefits or improvements to soil properties that occur as a result of soil compaction (Holtz and Kovacs, 1981):

- Increases in soil strength and slope stability.
- Improvement of bearing capacity in pavement subgrades.
- Reduction and/or prevention of soil settlement.
- Minimization of volume changes due to frost action, swelling, and shrinkage.

To determine and/or quantify the required engineering soil properties for field compaction, engineers compare field compaction to laboratory soil compaction. In 1933, the "Fundamentals of Soil Compaction" was published by R.R. Proctor. This publication established a relationship in laboratory soil compaction between density, moisture content, and compaction effort. The Proctor method of compaction (Proctor tests) is still the primary laboratory soil compaction method used throughout the United States today.

Today's heavy equipment often produces soil dry unit weights which may not be attainable using Proctor impact tests. As construction equipment, methods, and technology have progressed, the degree of soil compaction in the field has dramatically increased. Contrary to field compaction, laboratory compaction methods (Proctor tests) have remained relatively unchanged since their conception. Additionally, the techniques and methods for compacting soil differ between the laboratory and field. Proctor tests use an impacting force to densify soil samples, while field compaction of soils is primarily achieved through one or more of the following actions: static force, vibration, kneading, tamping, and impact blows.

Problem Statement

The incentive for this study was to develop a new laboratory compaction method that yields a better correlation between laboratory soil compaction and modern field compaction. The experimental method chosen for this research effort utilized a Superpave Gyratory Compactor (SGC) to compact soil samples. The gyratory compactor was chosen due to the similarities in compaction motions between gyratory compaction and field compaction.

Gyratory compactors were initially developed in the late 1930s and have since evolved into the primary laboratory method of compaction for hot mix asphalt (HMA) in the United States. The SGC was designed to simulate orientation of aggregate, degradation of aggregate, field compaction, and traffic degradation that occurs in HMA during production, compaction, and traffic loading (Collins et al., 1997).

Objective / Scope

The main objective of this research was to determine if the SGC, which was designed for HMA compaction, is also a viable apparatus for laboratory soil compaction. A field compaction study was not incorporated into this study; therefore, gyratory compaction was not directly compared to field compaction. Instead, results from gyratory compaction were quantitatively compared to traditional laboratory compaction techniques such as Proctor tests.

A second objective of the study was to evaluate, and recommend a SGC soil compaction procedure. The SGC has several adjustable parameters that control the degree and rate of compaction. The effects of these parameters vary depending on soil type and moisture content. This project physically explored two SGC parameters (confinement pressure and number of gyrations) and their respective compaction results. Multiple soil types and moisture contents were compacted for each combination of parameters.

Thesis Organization

Following this chapter, Chapter 2 provides a literature review in regards to soil and gyratory compaction. The development of laboratory soil compaction as well as current and past gyratory compaction studies are explored and explained in Chapter 2. Chapter 3 discusses the laboratory methods used during this study. This includes geotechnical index testing, soil classifications, and gyratory compaction. Chapters 4 and 5 present and discuss the gyratory compaction results. Chapter 6 provides a summary of the analysis and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

Introduction

The first section of this literature review discusses the development and fundamentals of laboratory soil compaction. The second section of this chapter describes gyratory compaction, including the development and historical uses of the gyratory compactor, as well as modern applications of the SGC. The third section of this chapter reviews two previous studies that have used an SGC to perform laboratory soil compaction.

Soil Compaction

Soil compaction is defined, in simple terms, as the densification of soils by the application of mechanical energy (Holtz & Kovacs, 1981). Soil is compacted to improve the engineering properties of the soil, such as increased strength, increased stability, increased imperviousness, and reduced compressibility. These increases allow the soil to adequately support man made structures. To monitor the degree of soil compaction occurring in the field, engineers have developed laboratory soil compaction tests that serve as a metric for evaluating field compaction.

The fundamentals of laboratory soil compaction were established by R.R. Proctor in the early 1930s. Proctor developed a laboratory soil compaction test which could be related to soil compaction in the field. This test allowed engineers to determine the suitability of available soils, as well serve as a basis for control of construction operations

(Proctor, 1933). Today, the tests are commonly known as the Standard and Modified Proctor tests. The Proctor tests have helped engineers recognize that soil compaction is a function of four variables:

- Dry unit weight - Dry soil mass per unit volume. Common basis for judging the degree of compaction.
- Water content - Amount of water present in the soil voids relative to the amount of soil solids.
- Compactive effort - Mechanical energy imparted into the soil during compaction.
- Soil type - Each soil type has a unique particle structure which may cause it to compact differently.

Laboratory soil compaction is primarily achieved through impact and vibratory compaction. Field compaction is dependent on the type of soil being compacted. Fine grained soils such as clay are efficiently compacted using a sheepsfoot roller while granular materials generally achieve optimum compaction more easily using a vibratory roller. Pneumatic rubber-tired rollers apply a kneading compaction that can be used on both granular and fine grained soils. Impact compaction in the field is referred to as deep dynamic compaction which is used to stabilize deep deposits of soil. Deep dynamic compaction is achieved by dropping large weights from a substantial height. Table 1 shows some common methods of field and laboratory compaction. For each method displayed, a corresponding field and laboratory compaction techniques is listed.

Table 1: Comparison of Field and Laboratory Compaction Techniques

Method	Lab Simulation	Field Technique
Impact	Standard & Modified Proctor Test	Dropping Weight (Deep Dynamic Compaction)
Kneading	Harvard Miniature Test* Hveem Method*	Sheepsfoot Roller Rubber-tired Roller
Vibration	Vibratory Table (Relative Density Test)	Vibratory Rollers & Compactors
Static Compression	Compression Machine*	Smooth Wheel Rollers

* Experimental laboratory compaction methods studied by Rodriguez et al., 1988.

Table 1 lists several methods of laboratory soil compaction; however, the majority of laboratory compaction is performed using Proctor Compaction. Relative density is additionally used for free-draining soils.

Impact Compaction

The Standard Proctor Test was developed by R.R. Proctor in the 1930s and is a laboratory compaction test that densifies soil by imparting repeated impact loads into the soil. Impact loads are imparted into the soil from dropping a hammer a known number of times from a known height onto a soil that has been placed into a mold of a known volume. The dry unit weight of the compacted soil can be computed by dividing the mass of the soil in the mold by the volume of the mold. .

The Modified Proctor test was developed during World War II by the Army Corps of Engineers to better represent higher levels of soil compaction required under airport runways used to support heavy aircraft. This test is based on the standard Proctor test; however, it imparts more energy into the soil by using a heavier hammer and larger vertical drop. Details and specifications of the Standard and Modified Proctor tests are discussed in the methods section of this report.

Results from Standard and Modified Proctor tests can be used to produce a soil compaction curve that relates soil dry unit weight and moisture content. A maximum dry unit weight and optimum moisture content of a particular soil can be determined from the soil compaction curve. An example of the Proctor compaction curve is displayed in Figure 1. The maximum point on the curve in Figure 1 indicates optimum water content and maximum soil dry unit weight (density).

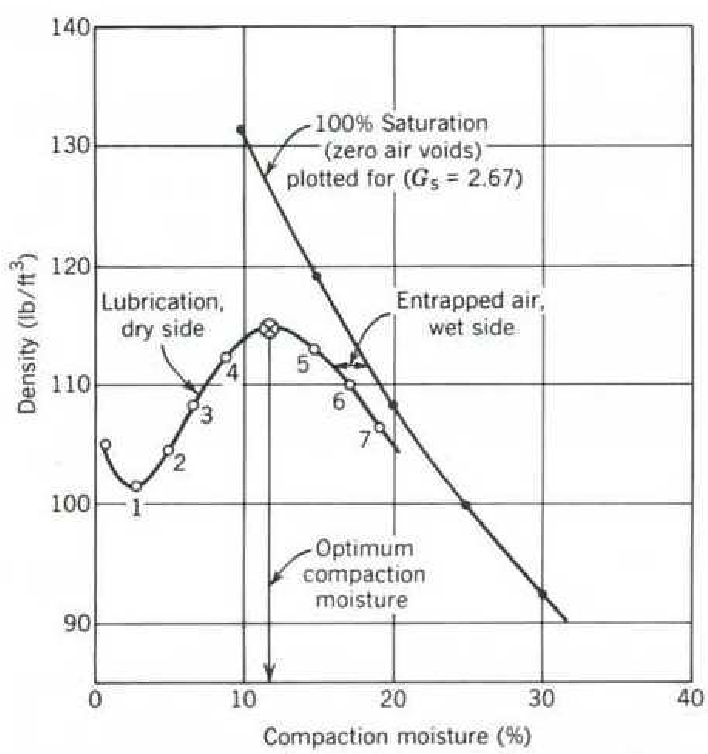

Figure 1: Example Proctor Curve (from Monahan, 1994)

The shape of the Proctor curve as well as the maximum dry unit weight and optimum moisture content will vary depending on soil type and energy imparted into the soil during compaction. Examples of how Proctor curves vary depending on soil type are displayed in Figure 2. Generally, for a particular soil, as the compaction energy of the test increases, the maximum dry unit weight will increase while the optimum moisture content will decrease.

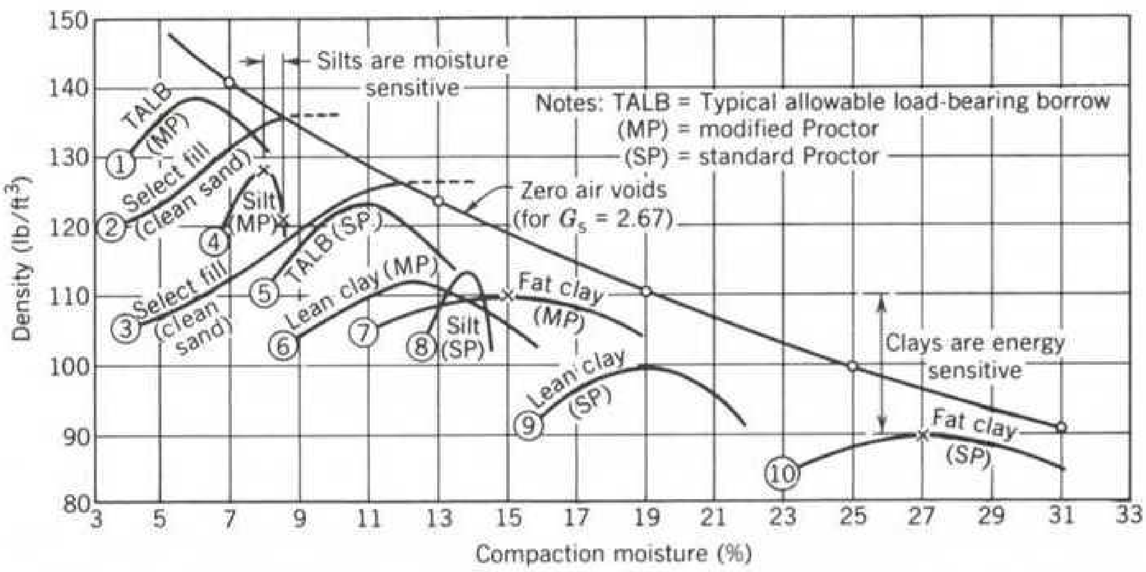

Figure 2: Proctor Compaction Curves for Spectrum of Soil Types (from Monahan, 1994)

Curves 2 and 3, in Figure 2, show typical Proctor compaction results of free-draining soils. These types of soils may not exhibit a optimum water content or show a consistent relationship between optimum water content and maximum dry unit weight (Johnson and Sallberg, 1962). Compaction curves are difficult to generate for free-draining soils, since the excess moisture can, in some cases, drain out of the Proctor mold prior to completing compaction and taking a moisture content reading. Free-draining soils often show the maximum dry unit weight occurring at the maximum moisture content (saturation). The American Society for Testing and Materials (ASTM) specifications for Standard and Modified Proctor tests state that if “this method [Proctor] is used for free-draining soils the maximum dry unit weight may not be well defined" (ASTM, 2003, p.165 & 227). ASTM D4253 recommends performing vibratory compaction tests in addition to Proctor tests to ensure that maximum dry unit weight was achieved (ASTM, 2003).

Vibratory Compaction

Free-draining soils usually do not produce a well defined maximum dry unit weight using Proctor tests; therefore, vibratory compaction procedures can be used in place of the Proctor test to determine maximum dry unit weight. The vibratory compaction test is intended solely for determining the maximum dry unit weight of cohesionless, free-draining soils. This maximum dry unit weight is usually higher than the maximum dry unit weight achieved with Standard or Modified Proctor tests. Some disadvantages of vibratory compaction include:

- Optimum moisture content cannot be determined, and
- The test can only be used to characterize cohesionless, free-draining soils.

Compaction in the field is often performed using vibratory compactors and rollers; therefore, vibratory compaction of laboratory soils often correlates to field conditions better than other laboratory compaction tests.

Gyratory Compaction

Texas Gyratory Press

Gyratory compaction was initially developed by the Texas Highway Department (currently the Texas Department of Transportation) in 1939 to aid in the design and control of asphalt mixtures (Harman et al., 2002). The Texas gyratory press was designed to compact soils and asphalt; however, the press evolved into primarily testing asphalt mixtures. A newer, modified Texas gyratory compactor has also been used to compact soil samples which were later used in laboratory swell tests (Sebesta, 2004).

A two part, trial and error compaction criterion was developed from 1939 to 1946. Part one of the criterion states that the gyratory compaction method must be equally adaptable to field control and design of the asphalt mix. Part two of the criterion states that the final product of the compaction should have similar densities and void ratios as the finished pavement exposed to traffic loading. An additional criterion was later established, which stated that the gyratory press should simulate aggregate degradation that occurs during field compaction (Harman et al., 2002). Research and experimental testing procedures were continually performed until 1946 when the Texas Highway Department established standard specifications and testing procedures for the Texas Gyratory Press.

The Texas Gyratory Press consisted of a four-inch steel mold that was manually gyrated. The mold was placed in the compactor at a 6 degree angle, and a vertical confinement pressure of 50 pounds per square inch (psi) was applied with a hydraulic jack. The mold was gyrated three times using a lever bar to rotate the mold in the gyratory press. After completing three gyrations, the gyratory angle was removed and the hydraulic jack, supplying the confinement pressure, was pumped one full stroke. If the full stoke of the jack failed to yield an increase to 150 psi, gyratory testing would continue. Testing would continue by reducing the confinement pressure back to 50 psi, resetting the angle of gyration to 6 degrees, and manually rotating the mold an additional

3 gyrations. This process would continue until one full stoke of the jack yielded an increase in confinement pressure to 150 psi. Once the endpoint of 150 psi was reached, a “level up” load of 2,500 psi was applied to the sample to complete the compaction (Huber, 1996).

In the late 1950s and early 1960s, a mechanized compactor was developed to simulate the mechanical press. A six-inch mold was also built for testing larger aggregate. The six-inch gyratory compactor utilized a different procedure in which the machine continuously gyrated, applied a constant vertical pressure, and continually tested the sample until “the rate of height change per revolution decreases below a specified limit” (Huber, 1996, p. 2).

Gyratory Testing Machine

The gyratory kneading compactor, now known as the Gyratory Testing Machine (GTM), was developed by John L. McRae of the United States Army Corps of Engineers (USACE) in the 1950s based on principles of the Texas Gyratory Press. The test was developed to simulate wheel path densities in asphalt concrete under heavy aircraft (Harman et al., 2002). USACE research had indicated that the Marshall Impact Hammer did not adequately simulate asphalt concrete properties or compaction that occurred on runways.

The Federal Highway Administration (FHWA) defines the GTM as “a combined compactor and plane strain shear testing machine for soils, unbound aggregates, and asphalt paving mixtures” (Asphalt Paving Technology, 2006). The GTM operates by applying a stress equal to that of a vehicle tire while monitoring the shear strain of the material during compaction. The USACE believed that the GTM would accurately account for asphalt and soil densification that occurred during construction, as well as the densification that occurred due to traffic loading post construction (Harman et al., 2002).

The GTM obtains an angle of gyration by using a two point system, which is different from the three point Texas Gyratory Press. The two point system allows the angle of gyration to flow (vary) throughout the compaction process. The changing angle throughout compaction can be related to permanent pavement deformation. The floating angle is measured during compaction and incorporated into the design procedure. The average angle of gyration is one degree (Harman et al., 2002).

Since its development in the 1950s, the GTM has been used for a variety of asphalt and soil testing. This literature review has focused primarily on the USACE use of the GTM to determine density requirements for subgrade and base materials of flexible pavements (Womack et al., 1969 and U.S. Army Corps of Engineers, 1962). Molding of large diameter triaxial specimens (Milberger and Dunlap, 1966) and using gyratory data to empirically calculate the resilient modulus (George, 1992) are two additional gyratory compaction tests on soil that have been performed using the GTM. A general gyratory compaction outline of the USACE procedure (U.S. Army Corps of Engineers, 1962) is as follows:

1. Obtain representative sample of base or subgrade material.
2. Match water content of the sample to the anticipated water content of the field material immediately after construction.

3. Calculate theoretical vertical pressure versus depth for the anticipated wheel loading. Assume circular tire loading.
4. Mix soil sample to the desired water content and compact sample in the GTM to 500 gyrations at a gyration angle of 1 degree and the vertical confinement pressure calculated in Step 3.

Results of the GTM testing are presented by plotting dry density (on the y-axis) versus the number of gyrations (on the x-axis). On the plot, the point where the next 100 revolutions causes an increase in dry density of 1 pound per cubic foot (pcf) marks the density that will be required for field construction. An example of this GTM plot is displayed in Figure 3. The multiple lines in Figure 3 each stand for a unique confinement pressure that was used to represent the theoretical tire pressure of a B-52 Aircraft at different soil depths.

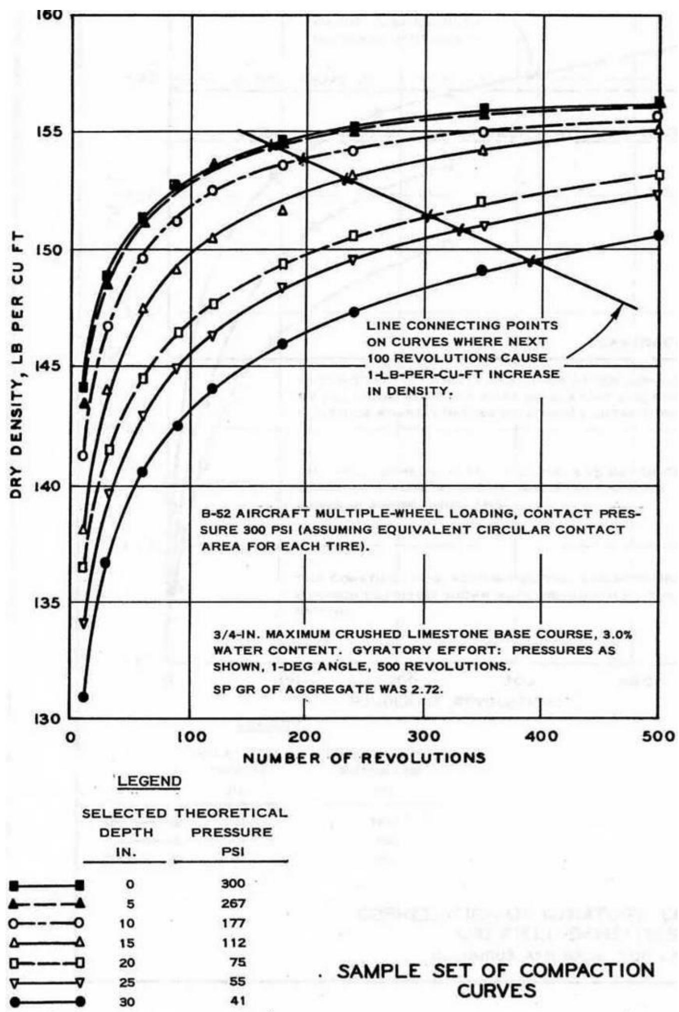

Figure 3: Typical GTM Compaction Data (from U.S. Army Corps of Engineers, 1962)

The USACE states that densities obtained using this GTM procedure correlate better with after traffic densities than the modified AASHO (now AASHTO) compaction tests (Modified Proctor tests) (U.S. Army Corps of Engineers, 1962).

LCPC Gyratory Compactor

In the 1960s and early 1970s the Laboratoroire Central des Ponts et Chausées (LCPC) of France developed a gyratory compactor for HMA use known as the PCG. The first version of the PGC (the PGC1) was developed using concepts from the Texas Gyratory Press. Studies performed while developing the PGC1 evaluated the shape of the gyratory densification curve and the changes in slope and position of the densification curve due to changes in aggregate gradation, mineral filler content, and varying asphalt properties (Huber, 1996). The FHWA defines the LCPC as "a gyratory compactor used to pre-evaluate asphalt mixtures for resistance to permanent deformation and to evaluate the workability of an asphalt mixture" (Asphalt Paving Technology, 2006).

Currently, the LCPC has developed and released the PGC3. The PGC3 is designed to meet all European, French, and United States (Superpave) standards. LCPC defines the PGC3 as "an apparatus which subjects the materials to simultaneous effects of compression force and kneading action through shearing which orients the grains of mineral skeleton" (Gyratory Shear Compacting Press, 2005). This process allows high densities to be reached at low compacting energy.

Superpave

The Superpave (*Su*perior *Per*forming Asphalt *Pave*ments) program, which was initiated by the Strategic Highway Research Program (SHRP) in the late 1980s, was a $50 million research effort to develop performance based tests and specifications for asphalt binders and Hot Mix Asphalt (HMA) (Roberts et al., 1996). As part of this research effort, the Superpave Gyratory Compactor (SGC) was developed to compact HMA samples to densities similar to that obtained in the field after construction and traffic compaction. The SGC was developed by evaluating and modifying previously mentioned gyratory compactors.

There are a variety of parameters which affect the degree of compaction achieved in the SGC (i.e., gyratory angle, confinement pressure, rate of gyration, and number of gyrations). These parameters affecting the SGC will be discussed in detail in the upcoming sections.

Gyratory Angle. During the development of Superpave, the Asphalt Institute conducted several studies analyzing the angle of gyration, rate of gyration, and vertical pressure. The Asphalt Institute concluded that density, for HMA, was most influenced by the angle of gyration.

Testing during the development of the SGC originally used a steep gyration angle of five degrees. Results utilizing the 5.0 degree gyration angle produced a rapid rate of compaction which yielded a densification curve that was difficult to interpolate/measure. Researchers then changed the gyration angle to 1.0 degree which matched the protocol of the French LCPC. This angle was found to be too shallow and did not allow a significant rate of densification. Eventually a 1.25 degree angle of gyration was selected. The 1.25 degree angle produced a reliable and easy to monitor compaction curve (Huber, 1996). The angle does not float like the GTM but remains constant throughout testing.

Because gyration angle was found to be the primary influence of compaction of HMA, SHRP researchers convinced FHWA to establish a very tight tolerance on the gyration angle. The current American Association of State Highway and Transportation Officials (AASHTO) T312 standard states the SGC must maintain a gyration angle of $1.25 \pm 0.02°$ throughout the compaction process (AASHTO, 2003).

Confinement Pressure. Vertical confinement pressure was found to have little effect on the density of HMA (Huber, 1996). Superpave designated using a 600 kilopascal (kPa) confinement pressure based on the PG3 compactor, as well as the similarity to vehicular tire pressure. The LCPC protocol for the PG3 compactor used a 600 kPa confinement pressure. This protocol produced consistent and reliable HMA density results.

Simulating laboratory compaction to field compaction and vehicle loading was an additional desire of Superpave. The Superpave designated that a 600 kPa confinement pressure accurately simulates pressures applied to the HMA during initial compaction as well as pressures applied during vehicular loading. Typical tractor-trailer tires are inflated to 552 kPa which applies a contact pressure of 552 kPa onto the HMA.

Rate of Gyration. In past gyratory compactors, the rate of gyration was limited by the abilities of that particular machine. The rate of gyration was often controlled by regulating power to that machine. The more power supplied to the machine, the faster the machine would gyrate.

Testing of multiple gyration rates on modern gyratory compactors revealed that the rate of gyration had little affect on the compacted density of HMA samples (Huber, 2006). A relatively high gyration rate was desired to allow for minimal testing time. The Texas gyratory compactor had successfully used a rate of 30 gyrations per minute for a number of years; therefore, Superpave designated using a gyration rate of 30 gyrations per minute.

Number of Gyrations. Superpave does not have a set number of gyrations for compacting asphalt samples. The number of gyrations is unique to each asphalt mixture and is dependent on the forecasted traffic levels and the expected maximum air temperature at the construction location. Table 2 shows the values recommended by Superpave based on traffic level and air temperature. Traffic level is the predicted Equivalent Single Axle Loads (ESALs) over the design life of the HMA.

Table 2: HMA Selection of Number of Gyrations for SGC (from Roberts et al., 1996)

Design ESALs (millions)	AVERAGE DESIGN HIGH AIR TEMPERATURE											
	< 39°C			39-40°C			41-42°C			43-44°C		
	N_i	N_d	N_m	N_i	N_d	N_m	N_i	N_d	N_m	N_i	N_d	N_m
<0.3	7	68	104	7	74	114	7	78	121	7	82	127
<1	7	76	117	7	83	129	7	88	138	8	93	146
<3	7	86	134	8	95	150	8	100	158	8	105	167
<10	8	96	152	8	106	169	8	113	181	9	119	192
<30	8	109	174	9	121	195	9	128	208	9	135	220
<100	9	126	204	9	139	228	9	146	240	10	153	253
>100	9	143	233	10	158	262	10	165	275	10	172	288

Key: N_i (N-initial) – measure of mixture compactibility
N_d (N-design) – number of gyrations required to produce a density in the mix that is equivalent to the expected density in the field after the indicated amount of traffic
N_m (N-maximum) – number of gyrations required to produce a density in the laboratory that should absolutely never be exceeded in the field

Dalton (2000) has performed research using a SGC to characterize gyratory shear and volumetric mix design. Recommendations in this research state that “complete characterization…often requires a larger number of gyrations than required for design purposes” (Dalton, 2000, p. 2). HMA mixtures used throughout this research were routinely compacted to 275 to 300 gyrations. The twofold justification for compacting the HMA mixtures to a higher than average number of gyrations includes:

- The original SHRP researchers purposefully selected a low angle of gyration for the SGC so that the rate of densification of the mix would be slow enough to reliably monitor. Therefore, to monitor the entire compaction process, a large number of gyrations are required.
- In order to see if a mix will fail, it must be pushed to the point of failure. Failure does not occur within the recommended number of gyrations.

Compaction Energy: Compactive energy is not constant during gyratory compaction. SGCs are designed to compact at constant shear strain; therefore, compaction energy constantly varies throughout compaction in order to maintain constant shear. Stiffer mixtures in the SGC will require increased energy input to maintain the constant shear strain. Gyratory shear is a unitless stiffness property of the sample mixture. It is defined by Dalton (2000) as the measure of effort expended by the SGC to maintain the constant angle of gyration during compaction.

Because constant shear strain is applied throughout the compaction process, the rate of compaction in the SGC is dependent on aggregate characteristics such as gradation, particle shape, and texture (Anderson et al., 2002).

Newer SGCs, such as the Pine AFG1, are equipped with devices to measure gyratory shear, in addition to recording the specimen height. Currently, the measurement of gyratory shear is not required or mentioned in the gyratory compaction AASHTO T312 specification (AASHTO, 2002). Experimental research has used gyratory shear, which is volume sensitive, as a mix design tool and/or quality control (Dalton, 2000). Empirical relationships have also been developed, using gyratory shear, in efforts to quantify energy imparted into an HMA sample during compaction. The Pine AFGC125X gyratory compactor used in this study is not capable of measuring gyratory shear or compaction energy.

Past efforts to quantify the energy/force required to apply and maintain a 1.25 degree angle of gyration include; indirectly inferring the energy consumption from changes in the specimen volume, measuring the torque on the motor driving the gyratory motion, and monitoring the electrical power consumption of the compactor itself (Dalton, 2000). These efforts were primarily experimental research that produced limited success.

Repeatability

Multiple studies have been performed looking into the statistics and repeatability of SGCs. An internal investigation report by Pine Instrument Company states that Pine models AFG1 and AFGC125X provide uniform consistent and repeatable results (Dalton, 1999). The report also states that there is a good correlation between the two Pine models as well as good correlation between new machines and machines which had seen years of service.

A comparison of the initial, design, and maximum densities using SGCs, from five different manufacturers, was performed by the Superpave Asphalt Research Program. This research reportedly took extreme care to only test the SGC without being influenced by additional factors such as: adherence to standard test procedures, material variability, operator proficiency, and compactor operating condition. Results indicated that all of the SGCs tested compared favorably with existing SGCs (McGennis, 1996).

To date, the author is unaware of a statistical analysis of repeatability using soil in SGC. Current analyses have only used HMA in the SGC. When using the SGC, there are many factors that affect HMA compaction but are not relevant with soil compaction. These factors include: calculation of Rice Specific Gravity (G_{mm}) and Bulk Specific Gravity (G_{mb}), temperature during preparation and compaction, and asphalt aging during sample preparation. These differences make it difficult to directly compare statistics of HMA compaction to soil compaction, and were some of the incentives behind this study.

Aggregate Degradation

The SGC was designed to approximate aggregate degradation and orientation that occurs during HMA mix production, field compaction, and traffic degradation. Collins et al. (1997) evaluated the effect of aggregate degradation on SGC compacted HMA samples. Two different aggregate sources were used during this study. The first source produced aggregate that experienced a high (52%) LA abrasion loss. The second source produced aggregate that experienced a low (22%) LA abrasion loss.

Superpave has predetermined gradation limits that aggregates must meet in order to be used in HMA. Both aggregate sources were initially within these Superpave limits. The aggregates were gyratory compacted and then reanalyzed to determine particle degradation. Results indicated that both aggregates remained within the Superpave restricted zone requirements and no significant degradation occurred on either of the aggregates. The aggregate with the higher LA abrasion loss did experience a larger degree of degradation in the SGC test.

Summary of Gyratory Compaction

Gyratory compaction has significantly evolved since its conception in 1939. A timeline of significant developments and the agencies responsible for these developments are shown in Table 3. The table also shows parameters unique to each testing agency and its respective gyratory compactor. Some of the trends and differences of the parameters used by each agency are commented on in the following list.

- Sample diameter has varied between 101.6 mm and 160 mm. Smaller diameters were initially used but later increased to accommodate larger aggregate sizes. A sample diameter of 150 mm is commonly used today.
- Sample height is dependant on each agency. Some agencies have variable heights; some have ranges the height must fit in between while others have specified height that the sample will be compacted to.
- Each agency has recommended confinement pressures, gyration angles, and rates of gyration. These parameters combine to produce a unique compaction effort. The effects of these parameters are discussed earlier in this chapter.

Table 3: Evolution of Gyratory Compaction (adapted from Harman et al., 2002)

Timeline	Device/Agency	Specimen Size (mm)	Compaction Effort
1939	Concept, TX Highway Department	D – 101.6 H – 50.8	P – Unknown A – Manual S – Manual
1946	TX Highway Department	D – 101.6 & 152.46 H – 50.8 & 76.2	P – Variable A – Fixed 6° S – 60 rpm
1957	US Army Corps of Engineers, GTM	D –152.4 H – Variable	P – Variable A – Floating 0 to 3° S – Variable 12 to 18 rpm M – Heated mold
1960's	First Prototype Texas at LCPC, France	D – Unknown H – Unknown	P – Variable A – Variable S – Variable
1968	Second Prototype Texas at LCPC, France	D – 80 or 120 H – Variable	P – Variable A – Floating 0.5° to 5° S – Variable M – Heated mold
1974 to 1985	PCG1, PCG2 at LCPC, France	D – 160 H – fixed 80 to 300	P – 600 kPa A – Fixed 1° to 4° S – Fixed 6 rpm to 30 rpm M – Heated mold
1991	Modified Gyratory Shear Test Machine, FHWA	D – 152.4 H – 95.3	P – 600 kPa A – Fixed 0.5° to 3° S – 30 rpm
1991	Modified TX Highway Department, SHRP	D – 152.4 H – 95.3	P – 600 kPa S – Variable M – Heated mold
1993	SHRP / Superpave Gyratory Compactor, USA	D – 150 H – 115	P – 600 kPa A – Fixed 1.25° S – 30 rpm
1996	PCG3 at LCPC, France	D – 150 H – Fixed 100 to 160	P – Fixed 500 to 800 kPa A – Fixed 0.5° to 2° S – Fixed 6 to 30 rpm

Key: D – diameter, H – height, P – confinement pressure, A – external mold wall angle, S – speed of gyration, and M – heated mold

Gyratory Compaction of Soil

Laboratory Simulation of Field Compaction Characteristics

Ping et al. (2003) evaluated field and laboratory compaction characteristics of sandy soils. The objective of the study was to determine if laboratory compaction techniques could accurately represent modern field compaction. The laboratory compaction techniques evaluated during this study included: Standard and Modified Proctor tests, kneading compaction, gyratory compaction, and vibratory compaction.

Ping et al. (2003) determined that gyratory compaction was the only laboratory compaction technique that accurately represented field compaction. The research focused on adjusting parameters that control the SGC to produce laboratory compaction results that match characteristics of field compaction. This research effort was unique in that it focused on trying to match compaction achieved in the field rather than compaction achieved in the laboratory with the Standard and Modified Proctor tests. Parameters evaluated in attempting to match field compaction are:

- Vertical pressure (100, 200, 300, 400, and 500 kPa),
- Total number of gyrations (30, 60, and 90),
- Gyration angle (1.00 and 1.25 degrees), and
- Rate of gyration (20 gyrations per minute).

After testing the above parameters on four sandy soils using a Servopac SGC, Ping et. al. (2003) recommended using the SGC test parameters shown in Table 4 to replicate field compaction characteristics.

Table 4: Recommended Gyratory Test Parameters for Soil (Ping et al., 2003)

Vertical Pressure (kPa)	200
Gyrations	90
Gyration Angle (Degrees)	1.25
Gyration Rate (Gyrations/min.)	20

The study concluded that using a vertical pressure of more than 200 kPa was not an effective means of increasing the dry unit weight. Additional research was recommended to address the issue of water and to determine the optimum moisture content, as well as to establish a gyratory testing procedure.

To date, Ping et al. (2003) provide the only published information that could be located on the use of a SGC to compact soil. Other studies have used non-Superpave gyratory compactors to compact soil (U.S. Army Corps of Engineers, 1962 and Womack et al., 1969).

Determination of Optimum Moisture Content and Maximum Dry Density of Soils

The Rhode Island Department of Transportation is currently investigating the possibilities of determining the optimum moisture content and maximum dry density of soils using a SGC. Rhode Island is treating the soil samples the same as a Superpave asphalt mix for a medium to high volume road. The SGC parameters for this type of asphalt mixture are 75 gyrations at 600 kPa confinement pressure, 30 gyrations per minute, and a gyratory angle of 1.25° (Frament, 2005).

The objective of this study is to replace the Modified Proctor test with the SGC; therefore, SGC results were compared to Modified Proctor test results. Frament (2005) stated “replacing the Proctor test with the SGC would decrease overall time requirements of testing, minimize technician error, reduce the amount of equipment-generated error, and determine critical properties of sub-base materials" (p.6).

The Rhode Island study is currently in progress; therefore, results, conclusions, and recommendations are unavailable.

CHAPTER 3

EXPERIMENTAL METHODS

Materials

A suite of four soils was selected to use throughout this gyratory compaction study. Each of the soils selected for this study is unique in particle size, texture, mineral composition, and classification. Soil type is one of the four functions of soil compaction; therefore, the soils were selected to determine how gyratory compaction would affect the compaction characteristics of various soil types. These soils represent a wide range of soil types encountered in modern construction.

The four soils used in this study were classified in general accordance to the AASHTO Soil Classification System. The texture of the soils, in this study, range from sandy gravel to clay. Similar studies in Florida (Ping et al., 2003) have exclusively focused on sandy soils.

Manufactured soils were used when possible to maximize consistency throughout the series of testing. The A-3 and A-7-6 were manufactured in the laboratory. General descriptions as well as the composition of each of the four soils used throughout this study are shown in Table 5.

Table 5: Soil Classifications and Descriptions

AASHTO Classification	General Description
A-1-a	Crushed Chert from Mississippi which contains gravel, stone fragments, and sand.
A-3	Fine sand manufactured in the MSU lab by combining 91% concrete sand with 9% Baghouse Fines, by weight.
A-4	Natural silt material obtained from MSU's Agricultural Research Farm (Post Farm) located 5 miles west of the MSU campus.
A-7-6	Clay soil manufactured in the MSU lab by combining 80% Baghouse Fines and 20%Bentonite, by weight.

Geotechnical Index Testing

Geotechnical index tests are a series of laboratory tests used by engineers to determine basic soil properties and classifications. An entire suite of typical index testing was performed on the A-1-a and A-7-6 soils. Index values for the A-3 and A-4 soils were determined on a previous research project utilizing the same soils (Friðleifsson, 2005).

Atterberg Limits

The Liquid Limit (LL) and Plastic Limit (PL) tests were performed in general accordance to AASHTO T-89, on the two fine grained, cohesive soils used in this study (AASHTO, 2002). The Atterberg limit values are summarized in Table 6.

Table 6: Atterberg Limit Test Results

AASHTO Classification	LL	PL	PI
A-1-a	NP	NP	NP
A-3	NP	NP	NP
A-4	29.7	7.9	21.8
A-7-6	83.7	23.9	59.8

Note: NP = nonplastic soil

Soil Gradations

Mechanical sieve analyses were performed on each of the soils to determine soil gradations. A sieve analysis was conducted on each of the soils using U.S. Sieve sizes; 3/8”, #4, #10, #20, #40, #100, and #200. The sieves needed for AASHTO classification (#10, #40, and #200) and the amount of soil passing each of these sieves is shown in Table 7.

Table 7: Percent Soil Passing #10, #40 and #200 Sieves

Soil	Percent Soil Finer than		
Classification	#10 Sieve	#40 Sieve	#200 Sieve
A-1-a	20.3%	8.4%	3.5%
A-3	86.6%	43.1%	7.5%
A-4	99.6%	81.4%	57.4%
A-7-6	100.0%	99.9%	65.1%

Hydrometer tests were performed on the A-4 and A-7-6 soils to obtain the approximate particle-size distribution of soil particles finer than the No. 200 sieve. The sieve analyses and hydrometer tests were conducted on each soil sample in general accordance with ASHTO T-88 (AASHTO, 2002). Gradation curves for the four soils are shown in Figure 4.

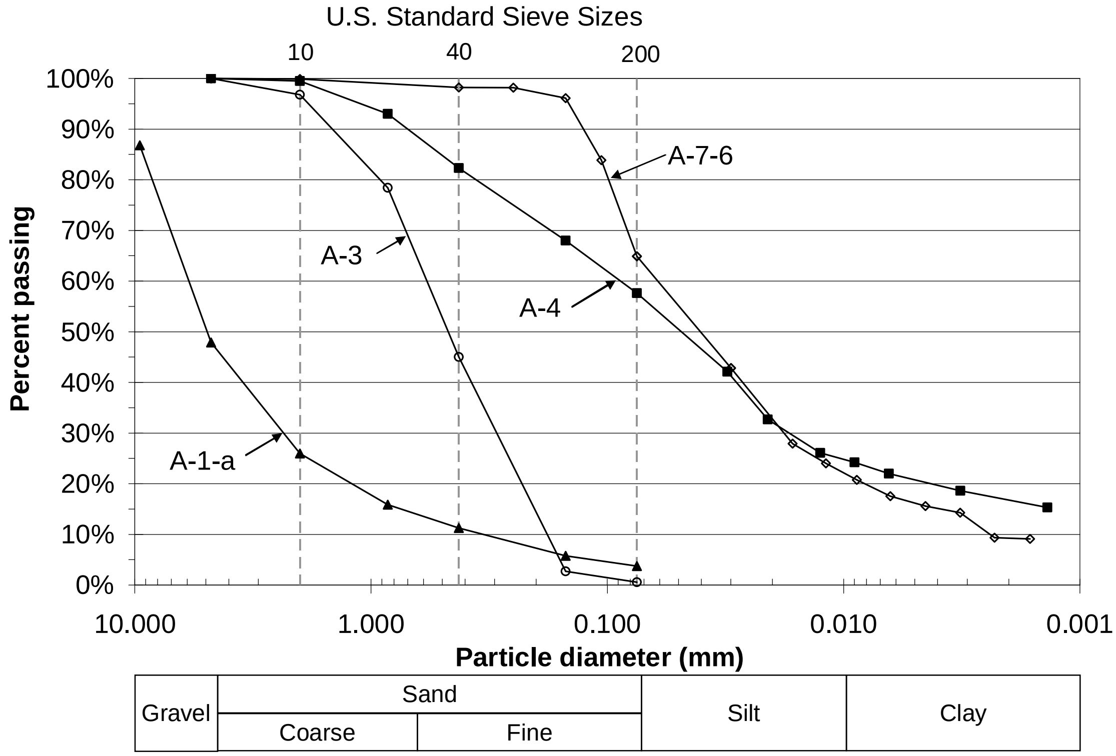

Figure 4: Gradations of Experimental Soils

Specific Gravity

Specific gravity (G_s) is a ratio of the unit weight of the soil solids (γ_s) to the unit weight of water (γ_w) (Equation 1). Specific gravity must be calculated to compute the soil void ratio and determine the hydrometer analysis. Specific gravity tests were conducted on the four soils in general accordance to AASHTO T 100 (AASHTO, 2002). Results of the specific gravity testing are shown in Table 8.

$$G_s = \frac{\gamma_s}{\gamma_w} \qquad (1)$$

Table 8: Specific Gravity of Soils

Soil Classification	G_s
A-1-a	2.68
A-3	2.63
A-4	2.66
A-7-6	2.65

Relative Density

Relative density tests are used to determine the degree of compaction of granular soils in the field. It is used to determine the state of dry unit weight of a cohesionless (granular) soil with respect to its maximum and minimum dry unit weights (Bowles, 1992). Relative density can be expressed in terms of dry unit weight (Equation 2) or void ratio (Equation 3). Relative density tests were conducted in general accordance to ASTM D4254 on each of the four soils (ASTM, 2003).

$$D_R(\%) = \left(\frac{\gamma_d - \gamma_{d(\min)}}{\gamma_{d(\max)} - \gamma_{d(\min)}} \right) \cdot \left(\frac{\gamma_{d(\max)}}{\gamma_d} \right) \cdot 100 \tag{2}$$

$$D_R(\%) = \left(\frac{e_{\max} - e}{e_{\max} - e_{\min}} \right) \cdot 100 \tag{3}$$

where γ_d is the *in situ* dry unit weight of the soil, $\gamma_{d(min)}$ is the dry unit weight in its loosest state, $\gamma_{d(max)}$ is the dry unit weight in the densest state, e is the *in situ* void ratio, e_{max} is the void ratio of the soil in its loosest state, and e_{min} is the void ratio of the soil in its densest state.

Although relative density testing is intended to be used exclusively with cohesionless, granular soils, relative density testing was also performed on the cohesive soils used in this study (A-4 and A-7-6). This was done solely to provide additional laboratory compaction results with which to compare to gyratory compaction. Results of relative density testing of the soils in a dry state are shown in Table 9. The minimum dry unit weight obtained from relative density testing is not displayed for the two cohesive soils (A-4 and A-7-6), due to the values having little meaning.

Table 9: Maximum and Minimum Void Ratios and Relative Density Dry Unit Weights

Soil Classification	e_{min}	e_{max}	$\gamma_{d(max)}$ (kN/m^3)	$\gamma_{d(min)}$ (kN/m^3)
A-1-a	0.67	0.93	15.77	13.61
A-3	0.41	0.68	18.47	15.55
A-4	0.81	1.24	14.19	-
A-7-6	1.02	1.48	12.88	-

<u>Proctor Compaction</u>

Standard and Modified Proctor tests are laboratory compaction tests used to determine the maximum dry unit weight and optimum moisture content of soil. The soil is compacted using mechanical energy obtained from an impacting hammer. The mechanical energy is a function of the hammer weight, height of the hammer drop, number of soil layers, and number of blows per layer. The parameters of the Standard and Modified Proctor tests are shown in Table 10.

Table 10: Standard and Modified Proctor Test Parameters

	Standard Proctor	Modified Proctor
Mold Volume (cm^3)	944*	944*
Hammer Weight (kg)	2.495	4.539
Hammer Drop (mm)	304.9	457
Soil Layers (#)	3	5
Hammer Blows per Layer (#)	25	25
Compaction Energy (kJ/m^3)	592.7	2,693.0

* Depending on soil gradation

Dry unit weight (γ_d) and moisture content ($w(\%)$) of the Proctor samples are calculated using Equations 4 and 5.

$$\gamma_d = \frac{W_s}{V} \tag{4}$$

$$w(\%) = \frac{W_w}{W_s} \cdot 100 \tag{5}$$

where W_s is the weight of soil solids, V is Proctor mold volume, and W_w is the weight of water.

To determine optimum moisture content and maximum dry unit weight, Proctor tests are generally performed on a particular soil at various moisture contents. The results of these individual Proctor tests are combined to develop a soil compaction curve which relates the soil dry unit weight to the moisture content of the soil. Figure 5 shows an example compaction curve for both the Standard and the Modified Proctor test. The Proctor curves presented in Figure 5 are example curves and do not represent any of the soils used in this study.

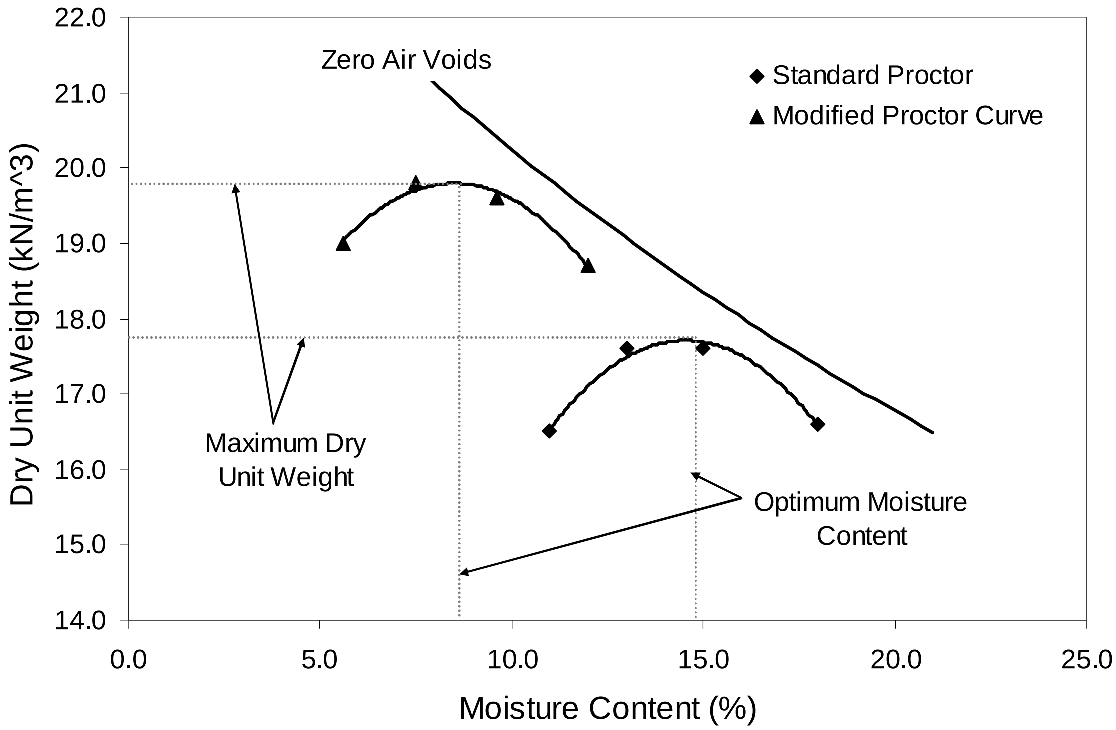

Figure 5: Theoretical Standard and Modified Proctor Curves

The maximum point on each curve in Figure 5 indicates optimum water content and maximum dry unit weight. Generally, the maximum dry unit weight will increase and the optimum moisture content will decrease as the compaction energy of the test increases.

Standard and Modified Proctor tests were performed in this study in general accordance to AASHTO T 99 and AASHTO T 180, respectively (AASHTO, 2002). Results from the Proctor tests are shown in Table 11. Standard and Modified compaction curves, for each of the soil types, are shown with the gyratory testing results in Chapter 4.

Table 11: Standard and Modified Proctor Maximum Dry Unit Weights and Optimum Moisture Contents

Soils	Standard Proctor		Modified Proctor	
	Max Dry Unit Weight (kN/m^3)	Optimum Moisture (%)	Max Dry Unit Weight (kN/m^3)	Optimum Moisture (%)
A-1-a	17.45	9.3	18.64	8.7
A-3	17.45	12.0	18.39	11.0
A-4	16.89	16.4	18.47	14.0
A-7-6	15.10	19.35	16.30	16.5

Gyratory Compaction

Currently there is not an AASHTO or ASTM standard for compacting soils with a SGC. The development of the test procedure used during this study has been a trial and error process. This trial and error procedure was based on a combination of the asphalt gyratory testing standard AASHTO T312 (AASHTO, 2002) and past soil compaction procedures utilized by the US Army Corps of Engineers (1962) and Ping et al. (2003).

Gyratory testing was performed in two phases. The initial phase tested the soils in a dry state at multiple confinement pressures on the SGC. The second phase involved testing soils at various moisture contents. The moisture content of these samples ranged from below optimum to above optimum moisture content as determined using Proctor tests.

Multiple SGC confinement pressures were used in both phase one and two of the laboratory testing. The SGC is capable of applying confinement pressures ranging from 200 to 999 kPa. The majority of testing during this study used confinement pressures ranging from 200 to 600 kPa. The position and direction the confinement pressure applied to the gyratory mold is shown in Figure 6.

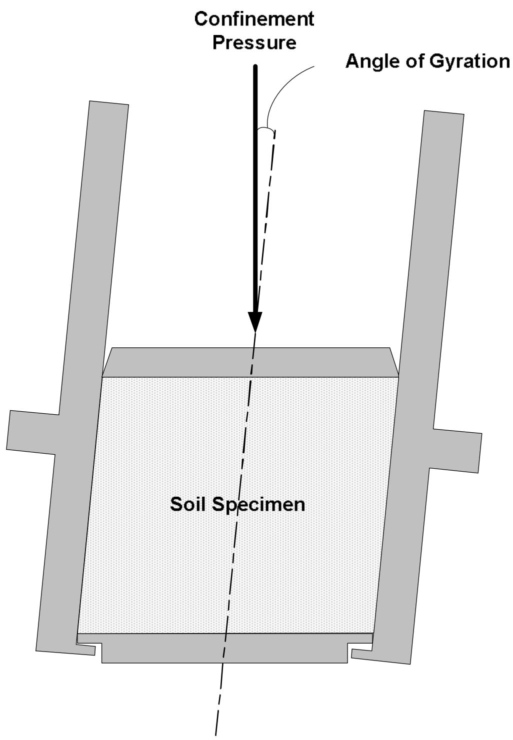

Figure 6: Position of Confinement Pressure, Angle of Gyration, and Soil Specimen with Respect to the Gyratory Mold

The 1.25° angle of gyration and gyration rate of 30 gyrations per minute (as recommended by Superpave) were used for all tests conducted under this research effort. The angle of gyration on the Pine AFGC125X SGC could only be altered by manually by adjusting the mold carriage links; therefore, it was decided to use only the preset 1.25° angle of gyration. The Pine AFGC125X SGC is only capable of running at the Superpave recommended 30 gyrations per minute; therefore testing at other rates of gyration was not available.

Phase I: Gyratory Testing of Dry Soils

Initial gyratory testing during this study focused exclusively on dry soils to simplify testing by eliminating variables related to moisture until a gyratory compaction procedure could be established. Variables within the SGC (confinement pressure and number of gyrations) were explored on a experimental basis. Preliminary test results indicated that confinement pressure had a unique effect on each of the soil types. Therefore, a decision was made to test multiple confinement pressures throughout the duration of this study. Testing of dry soils was also performed to determine if gyratory compaction of dry soils could produce dry unit weights that matched or surpassed Proctor dry unit weights.

Multiple gyratory tests were performed to a varying number of gyrations. These tests, as well as the literature review, indicated that the degree of soil compaction was directly related to the number of gyrations tested on the soil. A decision was made to compact all samples to 500 gyrations. Because sample height is measured after each gyration, dry unit weight can be calculated for each gyration. This high number of gyrations also allowed a more thorough understanding of the relationship between dry unit weight and number of gyrations.

Sample Preparation. To ensure the samples were thoroughly dry, all of the soils were oven dried at 110° C and then cooled to room temperature prior to compaction. Any visible clumps of soil that appeared to dry together were broken up prior to compaction. The A-7-6 soil was composed of powder bentonite and baghouse fines that had never been exposed to water and was in a powder form during this dry testing.

Initially, sample sizes of 4500 to 5000 grams of soil were loosely placed into the gyratory mold one lift. These sample sizes were selected to match a previous gyratory study by Ian Frament (2005). 4500 grams of the fine grained soils (A-4 and A-7-6) would not loosely fit into the mold. Therefore, 4000 grams of fine grained soil was used per sample for the remainder of the study. 4500 gram samples of the granular soils (A-1-a and A-3) were used throughout the remained of the study. Regardless of sample size, the entire soil sample was placed into the mold and compacted in one lift.

Once the mold was filled with soil, it was placed into the gyratory compactor and compacted to 500 gyrations at the desired confinement pressure. Confinement pressures of 200, 300, 400, 500, and 600 kPa were used for each of the four dry soils. During compaction, height of the soil sample for each gyration was transmitted and recorded to be later analyzed. Details of this analysis are discussed in Chapter 4.

Phase II: Testing Moist Soils

To develop soil compaction curves, the test soils also compacted at various moisture contents using the SGC. Multiple moisture contents for each soil were compacted using the SGC to 500 gyrations at confinement pressures of 200 and 600 kPa only. This decrease in number confinement pressures tested was required to enable adequate laboratory testing time to complete a full suite of moisture content tests for each soil type. Confinement pressures of 200 and 600 kPa were selected to represent the maximum effects of confinement pressure on gyratory compaction.

Sample Preparation. Proctor compaction tests were performed on the four soils, prior to gyratory compaction, to determine the soils' optimum moisture contents. Moist gyratory compaction samples were thoroughly mixed with water at moisture contents ranging from the dry to wet of optimum moisture contents determined by the Modified Proctor test. Soils that contained cohesive fines were covered and stored overnight to allow adequate time for the water to penetrate the entire sample.

As with the dry soils, sample sizes of 4000 and 4500 grams of soil were used for cohesive and granular soils, respectively. The soil sample was placed into the mold in one lift. The mold was placed into the gyratory compactor and compacted to 500 gyrations at the desired confinement pressure (200 or 600 kPa). Compaction of the granular soils at high moisture contents caused water to be forced out of the soil and into the gyratory compactor. To account for this water loss, a second moisture content was taken from the soil in the mold after gyratory compaction had been completed.

CHAPTER 4

ANALYSIS AND RESULTS

Introduction

The experimental test results of gyratory compaction of soils are described herein. Compaction characteristics achieved using gyratory compaction were directly compared to those obtained using the Standard and Modified Proctor test methods. The effects of soil type, moisture content, and programmable gyratory compactor variables (confinement pressure and number of gyrations) are discussed in detail.

Calculation of Gyratory Compaction Characteristics

The sample height (h_i) is recorded by the SGC for every gyration (i). This sample height was used to calculate volumetric and unit weight data of the soil samples. This data was used to compare soil characteristics for various compaction techniques (gyrator, Proctor, & vibratory) for each soil type (A-1-a, A-3, A-4, A-7-6). The gyratory compaction results were analyzed to determine effects of each of the following variables:

- number of gyrations,
- confinement pressure,
- moisture content, and
- soil type.

A graphical relationship of the soil compaction as it occurs during testing was created by calculating the dry unit weight of the soil ($\gamma_{d(i)}$) for each gyration (i). The dry unit weight was calculated using Equation 6.

$$\gamma_{d(i)} = \frac{\left(\dfrac{M_t \cdot g}{\pi \cdot r^2 \cdot h_i}\right)}{(1+w)} \tag{6}$$

where M_t is the total soil sample mass, g is gravity, r is the interior mold radius, h_i is the height of the soil sample, and w is the soil moisture content in decimal form.

Other parameters were calculated using the gyratory compaction data so that they could be compared to known Standard or Modified Proctor dry unit weight values. The characteristics evaluated in this study included: slope of dry unit weight compaction curve, 10% air voids, void ratio, relative density, and relative compaction, as defined in Equations 7 through 11, respectively.

$$M = \frac{\left(\gamma_{d(i+100)} - \gamma_d\right)}{100} \tag{7}$$

$$N_a = \left[1 - \left(\frac{\gamma_d}{\gamma_w}\right) \cdot \left(\frac{1}{G_s} + \frac{w\%}{100}\right)\right] \cdot 100\% \tag{8}$$

$$e = \frac{G_s \cdot \gamma_w}{\gamma_d} - 1 \tag{9}$$

$$D_r(\%) = \left(\frac{e_{\max} - e}{e_{\max} - e_{\min}}\right) \cdot 100\% \tag{10}$$

$$RC_g = \frac{\gamma_{d(\max)}}{\gamma_{zav}} \tag{11}$$

where M is the slope of the compaction curve, $\gamma_{d(i+100)}$ is the dry unit weight at i plus 100 gyrations, N_a is the percent air voids, γ_w is the unit weight of water, G_s is the specific gravity, e is the void ratio, $D_r(\%)$ is the relative density, RC is the relative compaction, and $\gamma_{d(max)}$ is the maximum dry unit weight determined in the laboratory.

M is used to determine the number of gyrations where a 1 lb/ft^3 increase in dry unit weight is obtained over 100 gyrations. M was used by the USACE to determine when gyratory compaction was complete. Additional details about the USACE methods and M are discussed in Chapter 2.

N_a is defined as the ratio of the volume of air to the total volume of solids, water, and air (Trenter, 2001). *Na* is an experimental calculation used to evaluate field compaction conditions.

Relative compaction typically is used to evaluate the dry unit weight achieved in the field to the maximum dry unit weight achieved in the laboratory. Field compaction was not incorporated into this study; therefore, data for the maximum dry unit weight achieved in the field is not available. Consequently, for this study, relative compaction was calculated using the zero-air voids dry unit weight as the standard. This relative compaction was calculated according to Equation 11.

The zero-air voids dry unit weight is defined as the theoretical maximum value of dry unit weight which can occur; at a given moisture content (Das, 2004). The zero-air voids unit weight is calculated according to Equation 12.

$$\gamma_{zav} = \frac{\gamma_w}{\frac{1}{G_s} + w} \tag{12}$$

where γ_{zav} is the zero air voids dry unit weight.

Gyratory Compaction of Dry Soils

Dry soil samples of each of the four soil types considered in this study (A-1-a, A-3, A-4, and A-7-6) were compacted to 500 gyrations at compaction pressures of 200, 300, 400, 500, and 600 kPa. Unit weight compaction curves (UWCC) were created for each soil type to illustrate how the dry unit weight changes as the number of gyrations increase. These UWCC plots graphically illustrate the amount of compaction (dry unit weight) that is achieved during each gyration. Dry unit weight was calculated according to Equation 6 for each gyration (*i*). For comparison, the UWCC plots also show the maximum dry unit weights from Standard and Modified Proctor tests, and minimum and maximum density from vibratory compaction tests. These dry unit weights are shown as straight lines to indicate where each value intersects the UWCCs.

In general, the results showed that the ultimate dry unit weight increased as the confinement pressure and number of gyrations increased. Figure 7 through Figure 10 show the UWCC plots of dry unit weight versus the number of gyrations for soil types A-1-a, A-3, A-4, and A-7-6, respectively.

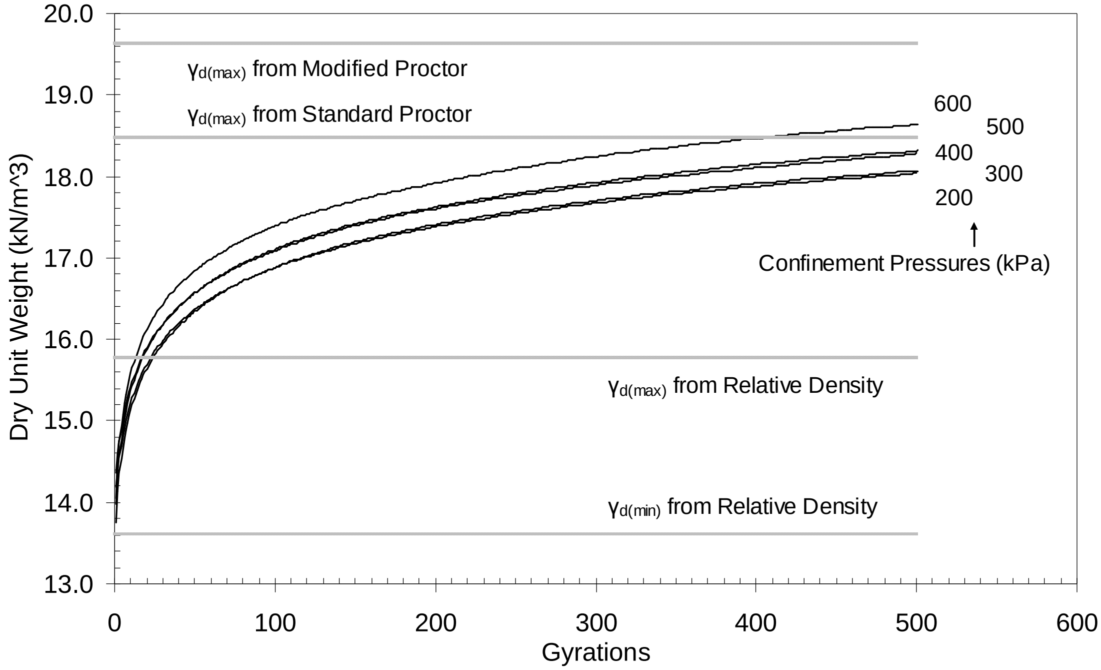

Figure 7: A-1-a Dry UWCC Plot for Multiple Confinement Pressures

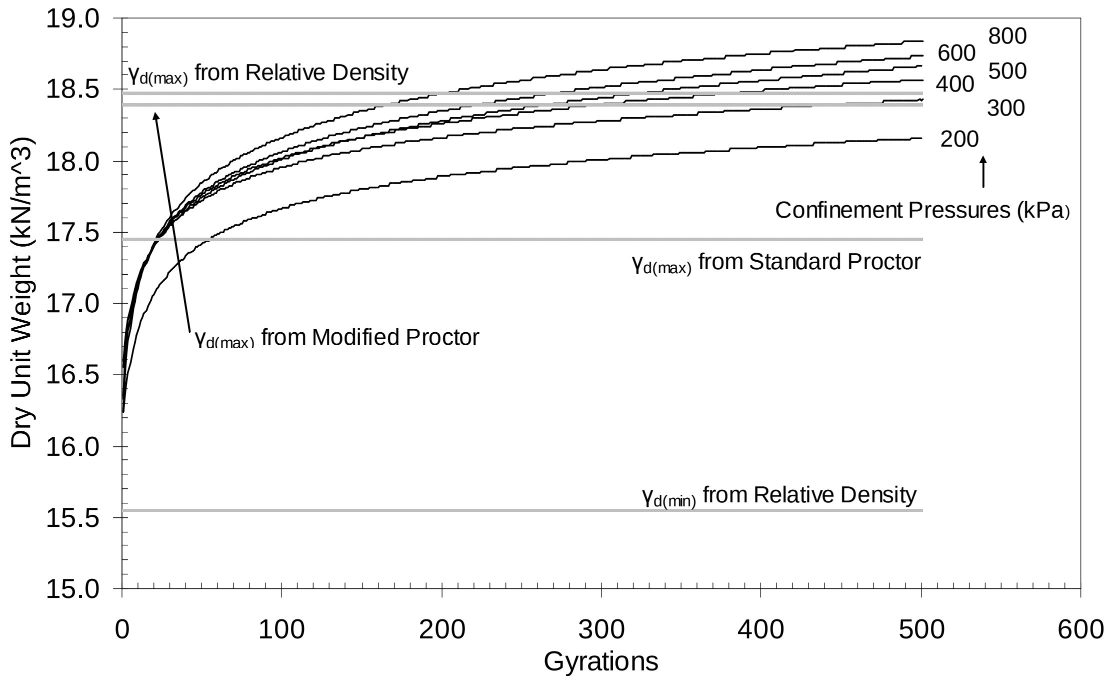

Figure 8: A-3 Dry UWCC Plot for Multiple Confinement Pressures

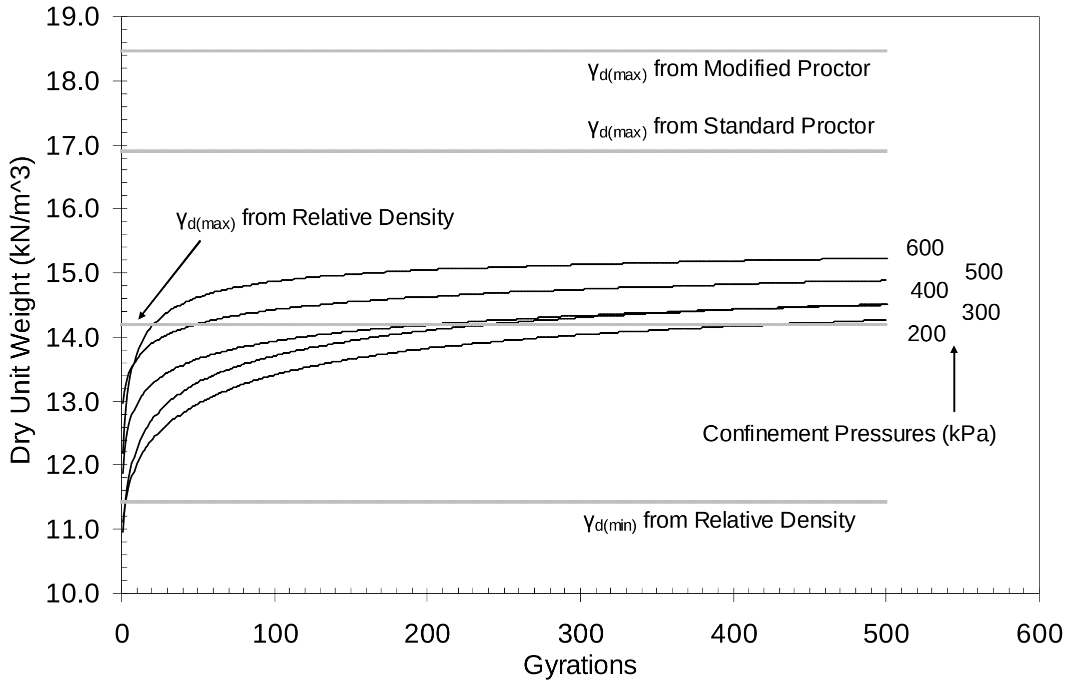

Figure 9: A-4 Dry UWCC Plot for Multiple Confinement Pressures

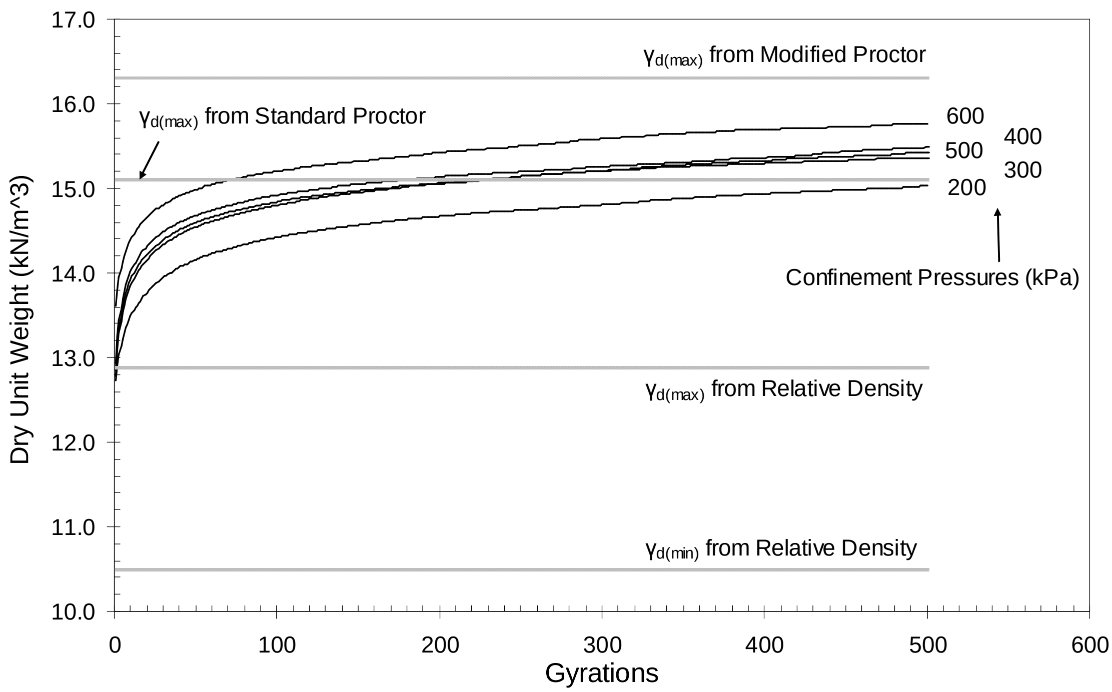

Figure 10: A-7-6 Dry UWCC Plot for Multiple Confinement Pressures

The A-3 soil, as shown in Figure 8, was additionally compacted at a confinement pressure of 800 kPa. The purpose of this additional pressure was to examine how confinement pressures greater than 600 kPa would affect compaction results. At 500 gyrations, 800 kPa confinement pressure did yield the highest dry unit weight achieved (18.86 kN/m^3). However, this ultimate dry unit weight was only 0.13 kN/m^3 higher than the 18.73 kN/m^3 achieved at 500 gyrations with a 600 kPa confinement pressure. During testing, abnormal sounds were made by the SGC when the 800 kPa confinement pressure was applied. These sounds did not occur at lower confinement pressures (200 to 600 kPa). Therefore, further testing was limited to a maximum confinement pressure of 600 kPa.

To numerically quantify the degree of compaction that occurs in Figure 7 through Figure 10; Table 12 through Table 15 were created to compare geotechnical index tests to gyratory dry unit weights. The tables illustrate the degree of compaction achieved at 500 gyrations using confinement pressures of 200, 300, 400, 500, and 600 kPa, defined as the ratio of the ultimate dry unit weight obtained from the SGC to the maximum dry unit weight obtained from the Standard Proctor, Modified Proctor, minimum density, and maximum density tests. The dry unit weights of each test are shown in parentheses.

Table 12: Comparative Analysis of Results for Dry A-1-a Soil Compacted at Multiple Confinement Pressures

Confinement Pressure & $\gamma_{d(ult)}$ at 500 Gyrations for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (17.47 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (19.64 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (15.77 kN/m^3)
200 kPa (18.04 kN/m^3)	103.3%	91.9%	114.4%
300 kPa (18.07 kN/m^3)	103.4%	92.0%	114.6%
400 kPa (18.28 kN/m^3)	104.6%	93.1%	115.9%
500 kPa (18.32 kN/m^3)	104.9%	93.3%	116.2%
600 kPa (18.64 kN/m^3)	106.7%	94.9%	118.2%

Table 13: Comparative Analysis of Results for Dry A-3 Soil Compacted at Multiple Confinement Pressures

Confinement Pressure & $\gamma_{d(ult)}$ at 500 Gyrations for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (17.45 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (18.39 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (18.47 kN/m^3)
200 kPa (18.16 kN/m^3)	104.1%	98.7%	98.3%
300 kPa (18.43 kN/m^3)	105.6%	100.2%	99.8%
400 kPa (18.57 kN/m^3)	106.4%	101.0%	100.5%
500 kPa (18.66 kN/m^3)	106.9%	101.5%	101.0%
600 kPa (18.73 kN/m^3)	107.3%	101.8%	101.4%
800 kPa (18.83 kN/m^3)	107.9%	102.4%	101.9%

Table 14: Comparative Analysis of Results for Dry A-4 Soil Compacted at Multiple Confinement Pressures

Confinement Pressure & $\gamma_{d(ult)}$ at 500 Gyrations for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (16.89 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (18.47 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (14.20 kN/m^3)
200 kPa (14.27 kN/m^3)	84.5%	77.3%	100.5%
300 kPa (14.52 kN/m^3)	86.0%	78.6%	102.3%
400 kPa (14.51 kN/m^3)	85.9%	78.6%	102.2%
500 kPa (14.89 kN/m^3)	88.2%	80.6%	104.9%
600 kPa (15.23 kN/m^3)	90.2%	82.5%	107.3%

Table 15: Comparative Analysis of Results for Dry A-7-6 Soil Compacted at Multiple Confinement Pressures

Confinement Pressure & $\gamma_{d(ult)}$ at 500 Gyrations for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (15.10 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (16.30 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (12.88 kN/m^3)
200 kPa (15.03 kN/m^3)	99.5%	92.2%	116.7%
300 kPa (15.36 kN/m^3)	101.7%	94.2%	119.3%
400 kPa (15.43 kN/m^3)	102.2%	94.7%	119.8%
500 kPa (15.49 kN/m^3)	102.6%	95.0%	120.3%
600 kPa (15.77 kN/m^3)	104.4%	96.7%	122.4%

Most of the soils (A-1-a, A-3, & A-7-6) were able to achieve the maximum Standard Proctor dry unit weight. A-3 was the only soil to achieve the maximum Modified Proctor dry unit weight. The dry unit weights achieved in the gyratory compactor were higher than expected considering no water was used to aid in compaction. The maximum Proctor dry unit weights were achieved at optimum moisture contents.

Slope of the Compaction Curve

Examination of Figure 7 through Figure 10 shows that the slope of the compaction curve varies depending on the soil type. The granular soils (A-1-a & A-3) appear to obtain the majority of their compaction in the first 100 gyrations although the dry unit weight continues to increase until compaction is terminated at 500 gyrations. The cohesive fine grained soils (A-4 and A-7-6) also appear to achieve the majority of their compaction initially but then taper off to a nearly horizontal slope.

A numerical comparison of the four soil types was created by calculating the tangent slopes of the compaction curves at 100 and 500 gyrations. The slopes of the compaction curves were calculated by taking the derivative of the best fit (logarithmic) line for each confinement pressure and soil type. Table 16 and

Table 17 show the average value and standard deviation of the gyratory compaction slope at 100 and 500 gyrations, respectively.

Table 16: Gyratory Compaction Slopes of Dry Soils at 100 Gyrations

	A-1-a	A-3	A-4	A-7-6
Average Slope (kN/m^3/gyration)	$7.40x10^{-3}$	$3.72x10^{-3}$	$4.39x10^{-3}$	$3.70x10^{-3}$
Standard Deviation	$2.57x10^{-4}$	$4.61x10^{-4}$	$1.24x10^{-3}$	$1.57x10^{-4}$

Table 17: Gyratory Compaction Slopes of Dry Soils at 500 Gyrations

	A-1-a	A-3	A-4	A-7-6
Average Slope (kN/m^3/gyration)	$1.48x10^{-3}$	$7.43x10^{-4}$	$8.78x10^{-4}$	$7.39x10^{-4}$
Standard Deviation	$5.14x10^{-5}$	$9.23x10^{-5}$	$2.48x10^{-4}$	$3.13x10^{-5}$

The compaction slopes for each of the soils in Table 16 are all the same magnitude. However, A-1-a slope is approximately twice as steep as the other soils. This indicates the A-1-a soil is still compacting when the other soils have already achieved the majority of their compaction at 100 gyrations.

Table 17 shows that the dry unit weight A-1-a soil is increasing at an order of magnitude rate higher that the other soils at 500 gyrations. The A-1-a soil continually increases in dry unit weight at a relatively steep compaction slope throughout the gyratory compaction process. Soils A-3, A-4, and A-7-6 have steep compaction slopes initially but then flatten out and approach horizontal. This indicates that small increases in dry unit weight are being achieved through additional gyrations.

Number of Gyrations versus Targeted Dry Unit Weight

In an effort to determine a Standard number of gyrations to compact soil samples to, results were additionally analyzed with the confining pressure on the y-axis versus gyrations on the x-axis. Viewing the data in this manner shows the number of gyrations required to reach a particular dry unit weight, such as Standard Proctor, for each confinement pressure tested. A downfall to this method is that a pre-determined dry unit weight must be selected to analyze the data, which may not always be known prior to compaction. Standard and Modified Proctor maximum dry unit weights were used to back calculate the number of gyrations necessary to reach this dry unit weight in the SGC. Confinement pressure versus number of gyrations for the A-3 soil are shown in Figure 11.

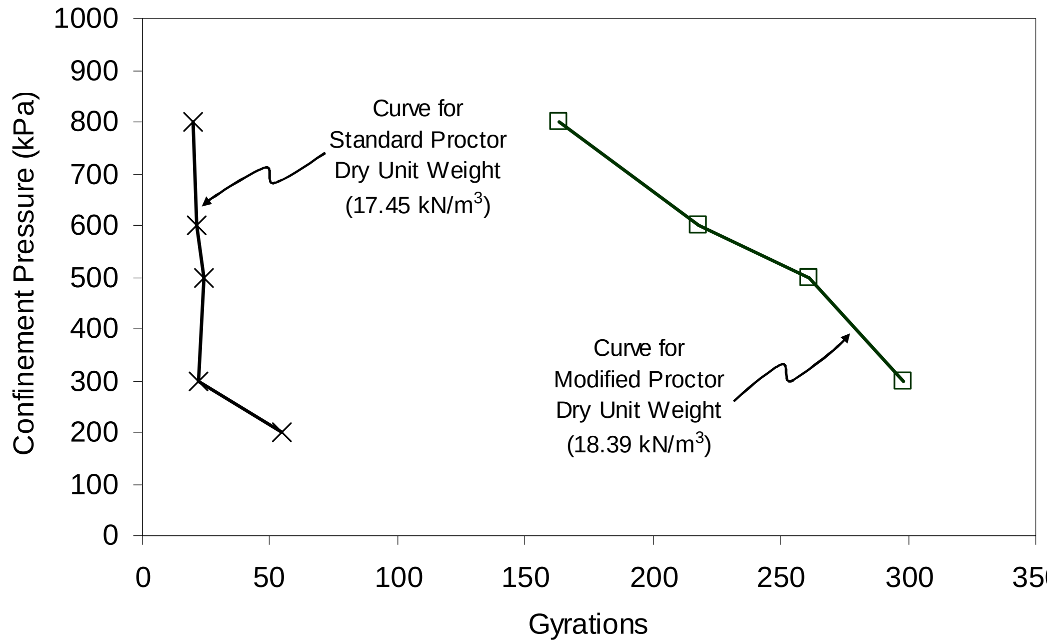

Figure 11: Number of Gyrations to Reach Proctor Maximum Dry Unit Weights at Multiple Confinement Pressures for the A-3 Soil

The other soils; A-1-a, A-3, and A-4 did not reach the Standard and Modified Proctor dry unit weights; therefore, these types of plots could not be created. Recall that these samples were compacted in the gyratory compactor in a dry state, where as the maximum dry unit weights for the Proctor tests were achieved at optimum moisture contents.

Presentation of the data in this format shows how changes in confinement pressure effects the number of gyrations required to reach a desired dry unit weight. Standard Proctor data points in Figure 11 occur at confining pressures of 300, 500, 600, and 800 kPa. Each of these confining pressures requires approximately 20 gyrations to reach the Standard Proctor dry unit weight of 17.45 kN/m^3. This data leads to the conclusion that increasing the confinement pressure above 300 kPa is not an effective method of decreasing the number of gyrations required to reach Standard Proctor dry unit weight.

However, Figure 11 also shows that increasing the confinement pressure does have an impact on the number of gyrations required to reach higher dry unit weights, such as dry unit weight from the Modified Proctor test.

Another method to examine the gyratory data is to analyze the slope of the compaction curve. The USACE compacts their samples until a termination point is reached. This termination point was defined as the slope of the compaction curve where the compaction rate reached 1 lb/ft^3 dry unit weight increase per 100 gyrations (U.S. Army Corps of Engineers, 1962). The slope of the gyratory compaction curve where this rate is reached was determined by Equation 7. The USACE method was applied to compaction data for each of the four soil types tested in this study. The numbers of gyrations to reach the USACE termination point for each confinement pressure and soil type are plotted in Figure 12.

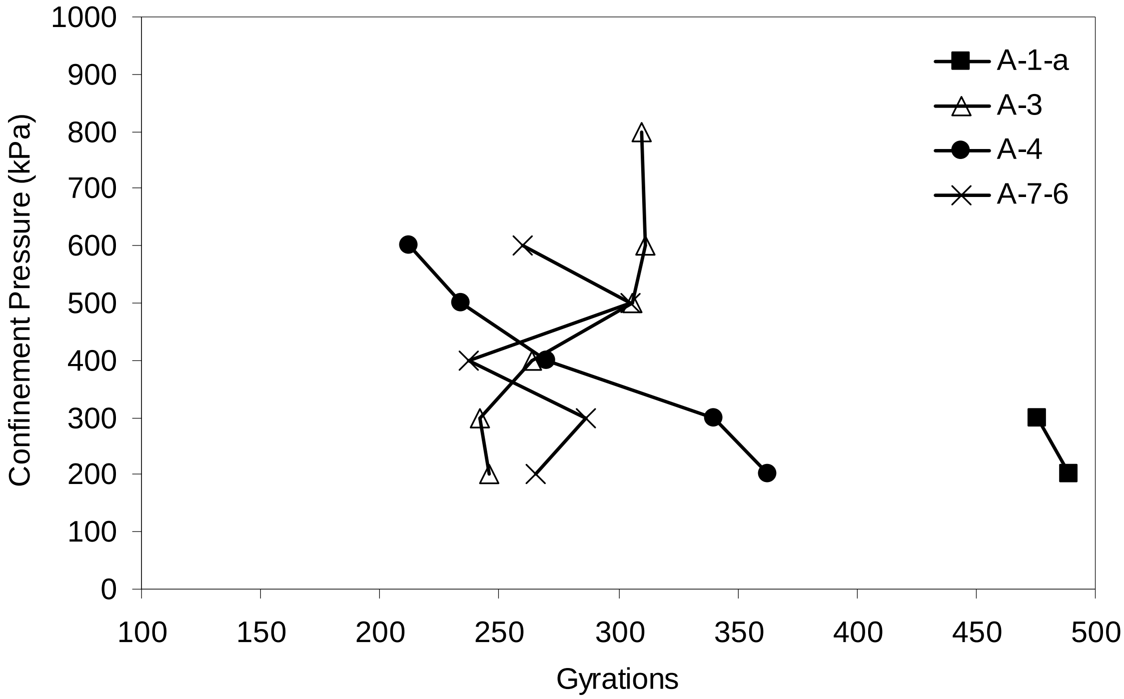

Figure 12: Gyrations versus Pressure for USACE Slope Method for All Soils

Figure 12 revealed that each of the soils tested during this study behaved and produced different results when analyzed using the USACE termination method.

The large grained, granular A-1-a soil only met the USACE requirements at low confinement pressures (200 & 300 kPa). Data points for confinement pressures of 400 kPa and higher are not shown due to the A-1-a soil continually increasing at a compaction rate which is higher than the USACE 1 lb/ft^3 increase per 100 gyrations cutoff. This high compaction rate is visibly displayed by the steeper slopes of the 400, 500, and 600 kPa confinement pressures in Figure 7. For the USACE requirement to be met, the A-1-a soil would have to be compacted to more than 500 gyrations. Data for soils in this study were recorded to 500 gyrations; therefore, it is unknown how many gyrations would be required to compact to the USACE termination point.

The A-3 soil met the USACE requirements on each of the compaction pressures tested. At low confinement pressures (200-400 kPa), the USACE termination point was met at approximately 250 gyrations. The higher confinement pressures (500-800 kPa) required approximately 320 gyrations. This required increase in gyrations indicates that a higher rate of compaction continues to occur for a longer period of time with higher confinement pressures.

The A-4 soil almost linearly decreases in the number of gyrations required to meet ASACE termination point as confinement pressure increases. This indicates that confinement pressure controls the rate of compaction for this silty soil. The higher the confinement pressure, the faster compaction occurs.

The A-7-6 soil does not display a definitive trend. The number of gyrations required to reach the USACE termination point appears to oscillate between 240 and 300 gyrations. The only conclusion that can be made for the A-7-6 soil is that on average, 270 gyrations are required to meet the USACE termination point.

Each of the soil types behaved differently when using the USACE method. In conclusion, the soils tested during this research exercise indicate:

- Fine grained soils should be gyratory compacted to 200 to 350 gyrations.
- Larger grained, granular soils require more than 500 gyrations.

There is variability in data points and trends from this arbitrary method; however, the data points due produce some rough trends and an approximate number of gyrations to compact a particular soil type. Additional soil types and compaction to more than 500 gyrations would enhance the trends of this method.

Gyratory Compaction of Moist Soils

To determine the optimum moisture content and maximum dry unit weight of the soils used in this study; the soils were also gyratory compacted at multiple moisture contents. These moisture contents varied depending on the soil but ranged from dry to wet of Proctor optimums (Standard and Modified). To simultaneously determine the affect of confinement pressure, the soils were compacted at 200 and 600 kPa confinement pressure.

As with the dry gyratory testing, UWCC plots were created to display the number of gyrations versus dry unit weight. These UWCC plots graphically illustrate the amount of compaction (measured in dry unit weight) that is achieved as the number of gyrations increase. The UWCC plots also show parameters obtained from other index tests (Standard Proctor, Modified Proctor, and Relative Density tests) as comparisons. Values of the index tests are shown as straight lines to show where the gyratory compaction curve intersects the index test dry unit weights. Two UWCC plots were created for each soil type. The UWCC plots display the gyratory compaction that is achieved at 200 and 600 kPa confinement pressures.

Optimum moisture content and maximum dry unit weight are not readily determining using the UWCC plots. Typical laboratory compaction curves, as shown in Figure 2 of the literature review, vary considerably depending on soil type and moisture content. To determine optimum moisture content using gyratory compaction, compaction curves were created to show dry unit weight versus moisture content. Compaction curve plots were created by picking the dry unit weight for all the moisture contents which occurred at a predetermined number of gyrations.

Compaction curves were created using the values of dry unit weight at 0, 75, 90, and 500 gyrations for each soil type and confinement pressure. Zero gyrations shows minimum compaction achievable in the SGC for a particular confinement pressure. This minimum compaction is achieved through confinement pressure without the aid of gyrations. The 75 and 90 gyration line represent the number of gyrations that Fremont (2005) and Ping et al., (2003) respectively used during their studies of gyratory compaction of soil. The 500 gyration line represents the maximum compaction achieved during this study.

Three sets of plots were created for each soil type. Each plot displays a different parameter that was evaluated in this study. General descriptions of these plots are:

1. Compaction curves generated at 200 kPa confinement pressure. Four compaction curves are displayed on this plot that show the dry unit weights achieved at 0, 75, 90, and 500 gyrations.
2. Compaction curves generated at 600 kPa confinement pressure. Four compaction curves are displayed on this plot that show the dry unit weights achieved at 0, 75, 90, and 500 gyrations.
3. Compaction curves at 500 gyrations for confining pressures of 200 and 600 kPa.

For reference, Standard and Modified Proctor compaction curves are also shown on these plots. The Proctor compaction curves are used as a point of comparison. The following soil sections explain the two UWCC plots and three compaction plots created for each soil type.

A-1-a Soil

Figure 13 and Figure 14 show the UWCC plots created for the A-1-a soil compacted at 200 and 600 kPa, respectively. Each figure contains multiple tests, each having unique moisture contents.

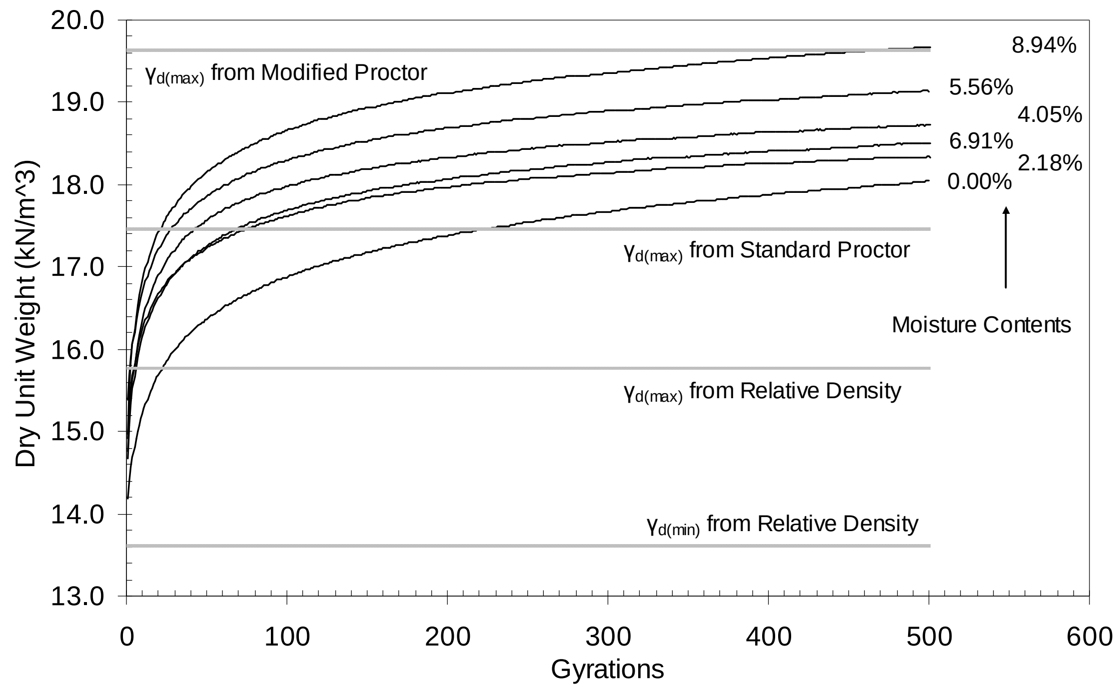

Figure 13: A-1-a UWCC Plot for 200 kPa Confinement Pressure and Multiple Moisture Contents

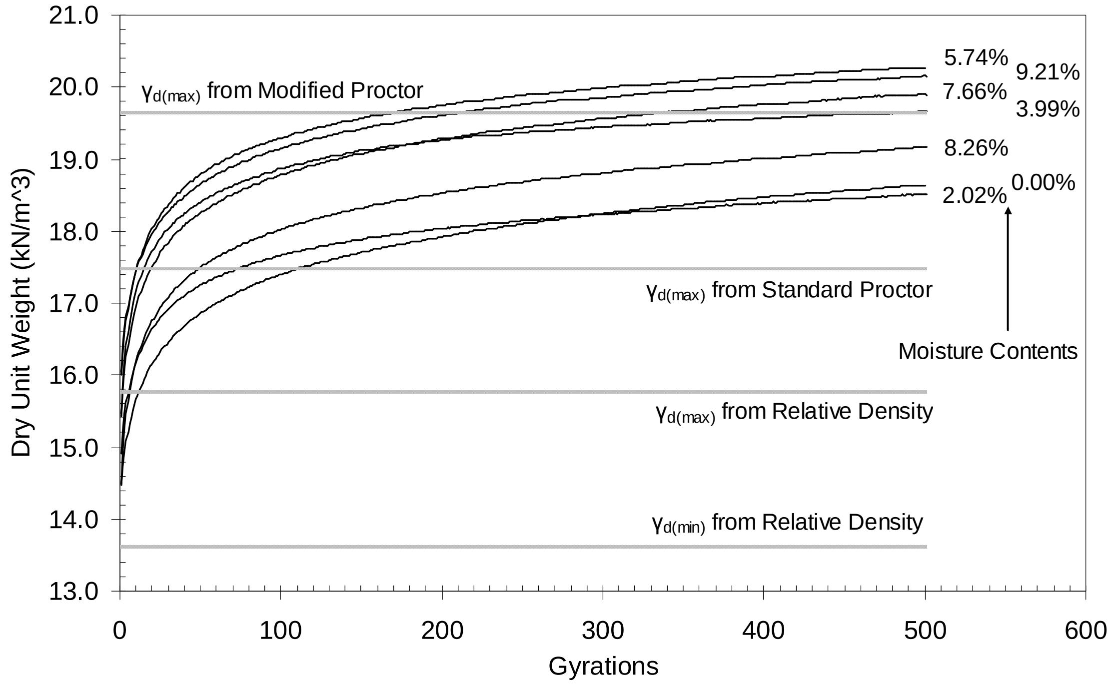

Figure 14: A-1-a UWCC Plot for 600 kPa Confinement Pressure and Multiple Moisture Contents

Comparison of Figure 13 and Figure 14 shows that confinement pressure does affect the amount of compaction for A-1-a soils. Soils tested at 200 kPa only had one test reach the Modified Proctor maximum dry unit weight. The majority of the samples tested at 600 kPa reached the Modified Proctor dry unit weight.

Figure 15 and Figure 16 show compaction curves created from the gyratory data at 200 and 600 kPa, respectively. The figures also display the Standard and Modified Proctor compaction results.

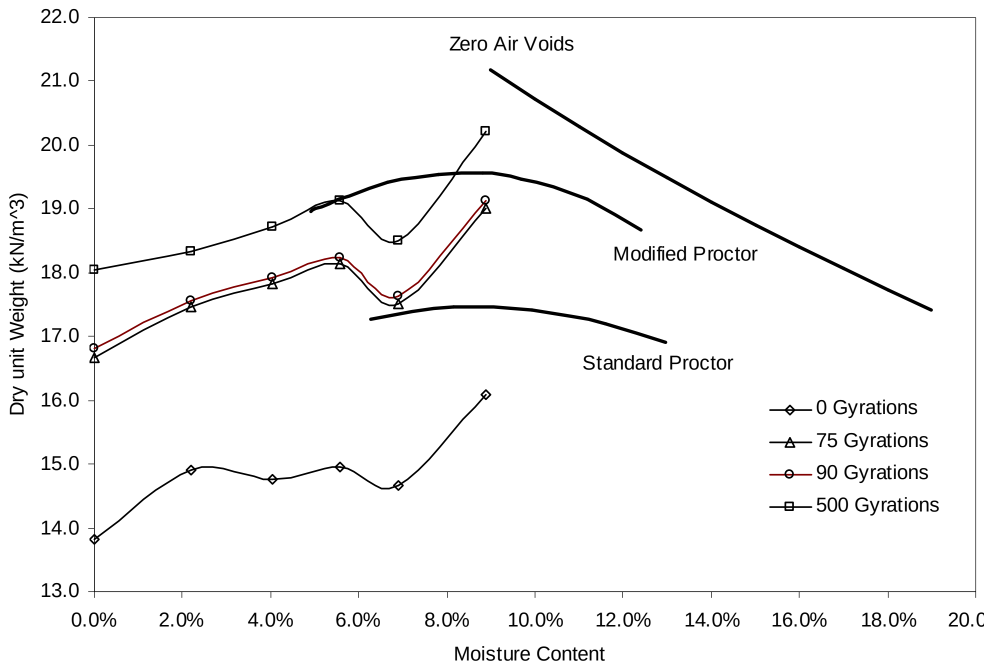

Figure 15: A-1-a Compaction Curve for 0, 75, 90, and 500 Gyrations at 200 kPa Confinement Pressure

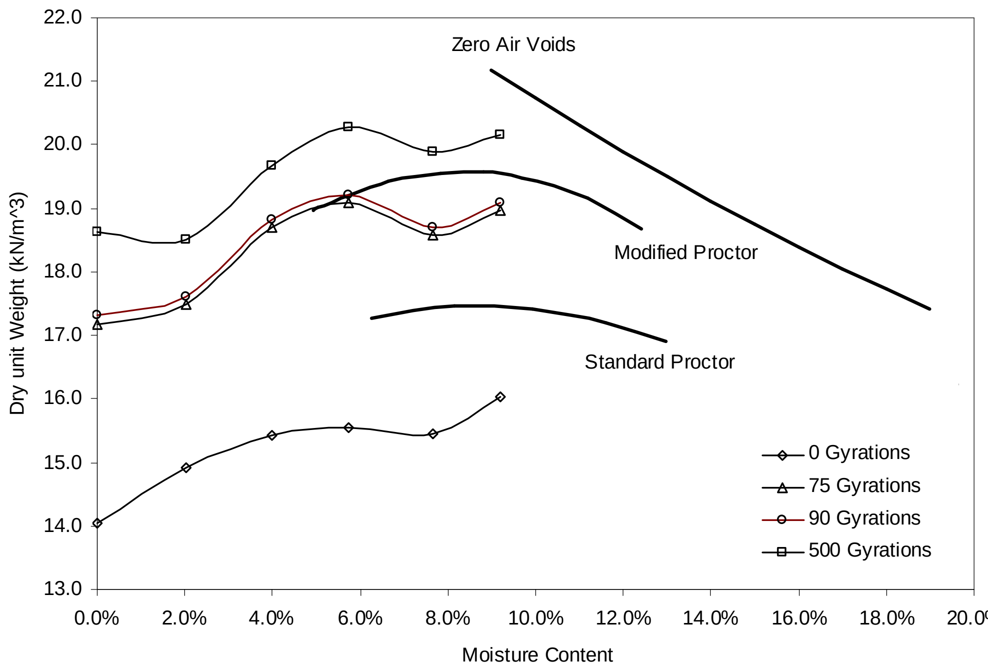

Figure 16: A-1-a Compaction Curve for 0, 75, 90, and 500 Gyrations at 600 kPa Confinement Pressure

Ideally, more gyratory tests should have been performed on soils wet of optimum; however, the A-1-a soil is relatively free-draining. The A-1-a would retain water up to approximately 8% moisture content. After this moisture content was reached, additional water was not retained in the soil mass. Like many free-draining soils, the soil does not have a well defined optimum moisture content or maximum dry unit weight. The general trend of the compaction curve shows that the material increases in dry unit weight as the water content is increased. Additional points on the wet side of optimum would likely show this more definitively; however, the soil is near saturation and has free standing water when it is mixed at 10 percent water content. Dry unit weights obtained from saturated or nearly saturated soils is questionable due to the difficulty of quantifying water loss during gyratory compaction. Water loss during gyratory compaction will be discussed in greater detail later.

Tabular comparisons between dry unit weights obtained from Standard and Modified Proctor tests, maximum relative density from vibratory compaction, and gyratory compaction are made in Table 18 and Table 19. These illustrate the degree of compaction achieved at 0, 75, 90, and 500 gyrations for confinement pressures of 200 and 600 kPa, respectively. The values represent the percentage of compaction achieved by the gyratory compactor compared to the index tests. They were obtained by dividing the dry unit weight of gyratory tests by the dry unit weight of the index tests (Standard Proctor, Modified Proctor, minimum relative density, and maximum relative density). The dry unit weights of each test were determined at optimum moisture contents and are shown in parentheses.

Table 18: Comparative Analysis of Results for A-1-a Soil Compacted at 200 kPa Confinement Pressure

Number of Gyrations & $\gamma_{d(ult)}$ for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (17.45 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (19.64 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (15.77 kN/m^3)
0 Gyrations (16.08 kN/m^3)	92.1 %	81.9 %	102.0 %
75 Gyrations (19.02 kN/m^3)	109.0 %	96.8 %	120.6 %
90 Gyrations (19.14 kN/m^3)	109.7 %	97.5 %	121.4 %
500 Gyrations (20.21 kN/m^3)	115.8 %	102.9 %	128.2 %

Table 19: Comparative Analysis of Results for A-1-a Soil Compacted at 600 kPa Confinement Pressure

Number of Gyrations & $\gamma_{d(ult)}$ for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (17.45 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (19.64 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (15.77 kN/m^3)
0 Gyrations (16.04 kN/m^3)	91.9 %	81.7 %	101.7 %
75 Gyrations (19.09 kN/m^3)	109.4 %	97.2 %	121.1 %
90 Gyrations (19.22 kN/m^3)	110.1 %	97.9 %	121.9 %
500 Gyrations (20.27 kN/m^3)	116.2 %	103.2 %	128.5 %

Figure 15 and Figure 16 as well as data comparisons made in Table 18 and Table 19 indicate that, in general, higher dry unit weights were achieved using gyratory compaction than Standard and Modified Proctor tests. At 200 kPa and 600 kPa confinement pressure, the gyratory compaction curve was able to surpass the Modified

Proctor maximum dry unit weight. For gyratory compaction to be a feasible replacement to the Proctor tests; dry unit weights achieved from gyratory compaction must be able to surpass Proctor dry unit weights.

Table 18 shows that at 75 gyrations, gyratory compaction achieved 109.0% and 96.8% of the Standard and Modified Proctor dry unit weights, respectively. At 500 gyrations, the same test achieved 115.8% and 102.9% compaction of Standard and Modified Proctor dry unit weights. The difference between the dry unit weight obtained at 75 and 90 gyrations of the A-1-a soil, compacted at 200 kPa confinement pressure, with respect to the Standard Proctor test is 6.8%. This difference, referred to as the Normalized Percent Difference (*NPD*), was calculated using Equation 13.

$$NPD = \frac{|\Delta \gamma_d|}{\gamma_{d(ref)}} * 100\% \tag{13}$$

where $\Delta\gamma_d$ is the change in the parameter of interest and $\gamma_{d(ref)}$ is the reference parameter used to normalize this difference. For the case mentioned above, $\Delta\gamma$, is the difference between the dry unit weight of the gyratory compactor at 75 and 500 gyrations at 200 kPa confinement pressure and $\Delta\gamma_{d(ref)}$ is the maximum dry unit weight obtained from the Standard Proctor test. An example calculation for this case is illustrated in Equation 14.

$$NPD = \frac{|20.21 - 19.02|}{17.45} * 100\% = 6.8\% \tag{14}$$

The *NPD* for gyratory compaction values between 75 and 500 gyrations at 200 kPa confinement pressure with respect to the Modified proctor test is 6.1%.

The same *NPD* comparison can be made in Table 19 between percent gyratory compaction of Standard and Modified Proctor dry unit weights for 75 and 500 gyrations.

The increase in gyrations from 75 to 500 results in an increase of 6.8% and 6.0% compaction of Standard and Modified Proctor dry unit weights, respectively. These comparisons indicate that increasing the gyrations can have a significant impact on the amount of compaction achieved.

The effects of confinement pressure are examined by comparing Table 18 to Table 19. At 500 gyrations, gyratory compaction performed at 200 kPa confinement pressure, achieved 115.8% and 102.9% compaction of the Standard and Modified Proctor dry unit weights, respectively. At 500 gyrations and 600 kPa confinement pressure, gyratory compaction achieved 116.2% and 103.2% compaction of the Standard and Modified Proctor tests, respectively. The *NPD* between the test at 200 and 600 kPa is 0.4% and 0.3%, respectively. These increases are solely due to increased confinement pressures. Comparison of these percent increases show that increasing the number of gyrations is the more effective than increasing confinement pressure to increase percent compaction.

The effect of confinement pressure during gyratory compaction of the A-1-a soil is dependent on the number of gyrations used. At 500 gyrations, the 200 and 600 kPa confinement pressures yielded maximum dry densities of 20.21 and 20.27 kN/m^3, respectively. The moisture contents for these maximum dry unit weights were 8.89% and 5.74%, respectively. Figure 17 shows optimum gyratory compaction at the 200 and 600 kPa confinement pressures.

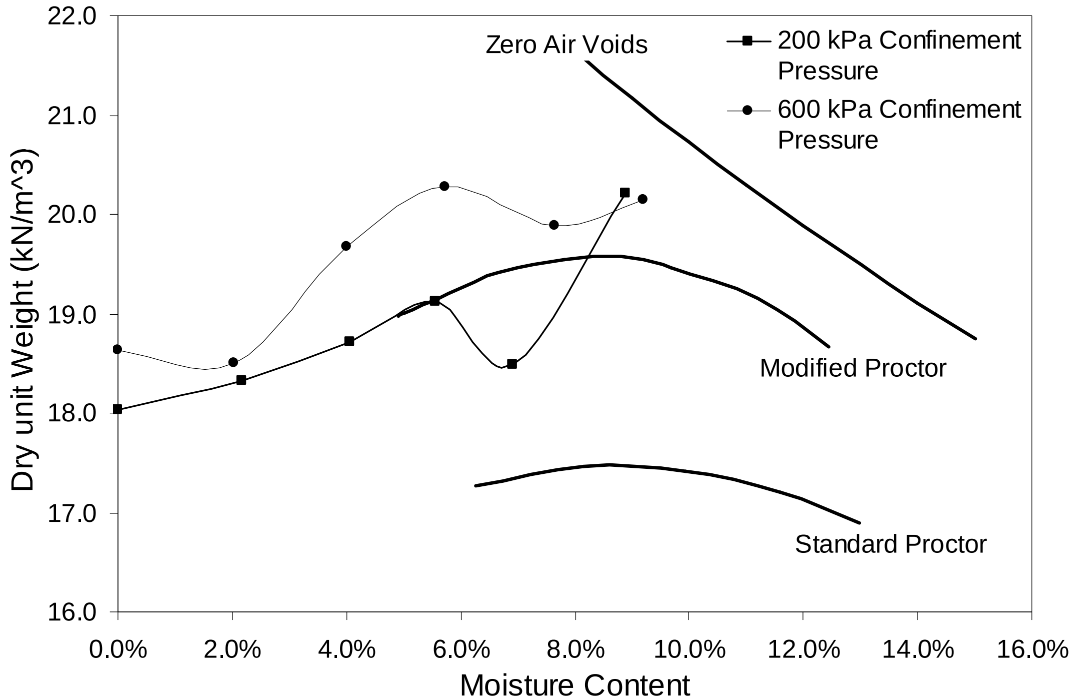

Figure 17: A-1-a Compaction Curve for 500 Gyrations at 200 & 600 kPa Confinement Pressures

A-3 Soil

Figure 18 and Figure 19 show the UWCC plots for A-3 soil which were compacted 200 and 600 kPa, respectively. Each figure contains multiple tests; each having a unique moisture content.

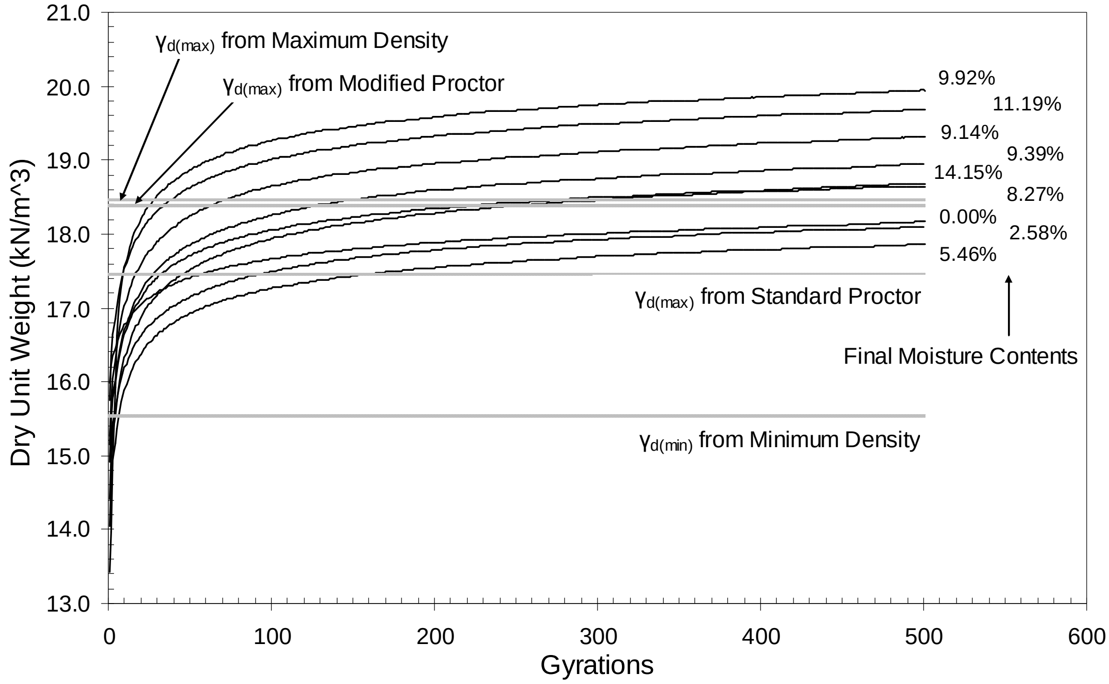

Figure 18: A-3 UWCC Plot for 200 kPa Confinement Pressure and Multiple Moisture Contents

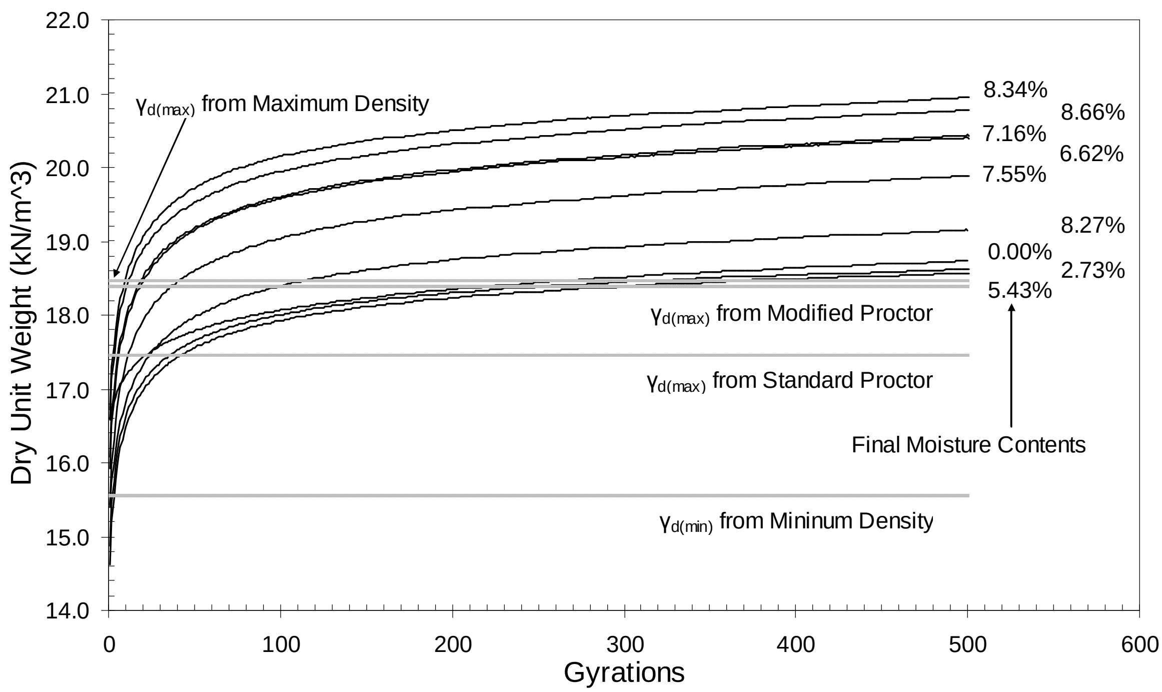

Figure 19: A-3 UWCC Plot for 600 kPa Confinement Pressure and Multiple Moisture Contents

Figure 18 and Figure 19 associated with the A-3 soil were created using moisture contents derived from the sample after gyratory compaction (displayed on the figures as Final Moisture Content). All other soils; A-1-a, A-4, and A-7-6 are plotted using the moisture content prior to gyratory compaction. The A-3 soil was the only free-draining soil that was compacted at moisture contents high enough to cause a considerable amount of moisture loss.

Comparing Figure 18 and Figure 19 show that confinement pressure does have an effect on the dry unit weight achieved. All of the moisture contents tested at 600 kPa surpassed the maximum relative density and Modified Proctor dry unit weight. Six of the nine moisture contents tested at 200 kPa surpassed the maximum density and Modified Proctor dry unit weight. As a result of increased confinement pressures, a higher degree of compaction was achieved with the moist soils than the soils tested in a dry state.

Figure 20 and Figure 21 display compaction curves (which relate dry unit weight and moisture content) created from the A-3 gyratory data for confinement pressures of 200 and 600 kPa, respectively. Compaction curves for the Modified and Standard Proctor tests are shown for comparison. Typical with free-draining soils, these Proctor curves are relatively flat.

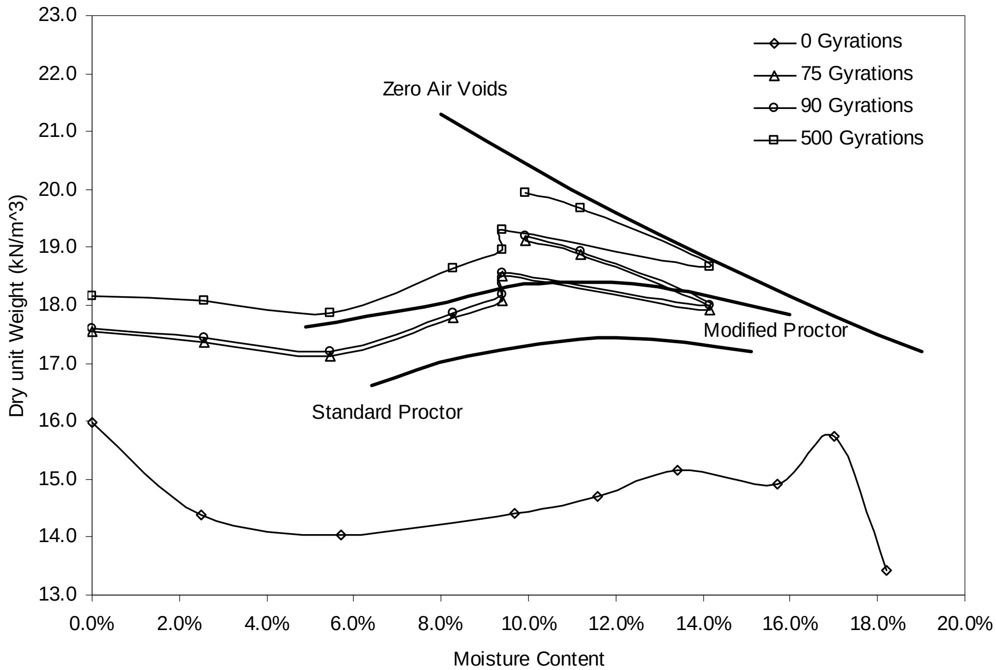

Figure 20: A-3 Compaction Curve for 0, 75, 90, and 500 Gyrations at 200 kPa Confinement Pressure

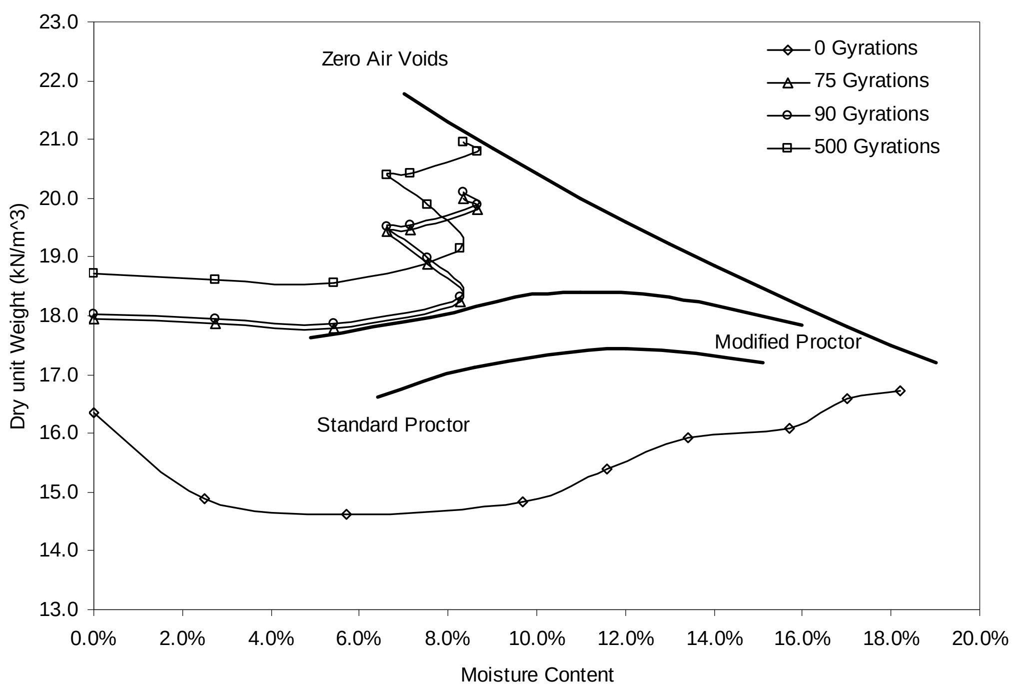

Figure 21: A-3 Compaction Curve for 0, 75, 90, and 500 Gyrations at 600 kPa Confinement Pressure

The zero gyrations compaction curve in both Figure 20 and Figure 21 was calculated and plotted using the initial moisture content of the sample as determined prior to gyratory compaction. The 75, 90, and 500 gyrations compaction curves were calculated and plotted using the final moisture content as determined after completion of the gyratory test. The 0 and 500 gyration, compaction curves are accurately calculated due to the initial and final moisture contents being known. Dry unit weights that occur at intermediate gyrations cannot be accurately calculated due to the uncertainty of the water content at that particular gyration. Separate gyratory tests, which will be explained in detail in an upcoming section, indicate that the majority of the moisture loss occurs before 75 gyrations for the A-3 soil. Therefore, dry unit weights for 75 and 90 gyrations were calculated using the final moisture contents.

Figure 20 and Figure 21 illustrate the amount of water which is lost during gyratory compaction. The gyratory compaction that takes place in Figure 21 appears to force all excess water out of the sample if the moisture content is above 7% to 9%. Samples that had initial moisture contents higher than 9% were forced down to the 7% to 9% range. A smaller percentage of water is lost during gyratory compaction at a 200 kPa confinement pressure than a 600 kPa confinement

The number of gyrations has a significant impact on the maximum dry unit weight achieved during gyratory compaction. The maximum dry unit weight achieved throughout all laboratory testing (Proctor, vibratory, and gyratory) of A-3 soils is 20.95 kN/m^3. The initial and final moisture contents of this sample were 18.2% and 8.34%, respectively. The high dry unit weight was achieved using the SGC at a confinement pressure of 600 kPa and 500 gyrations. The maximum dry unit weight achieved at 75 and 90 gyrations under these same parameters is 19.99 and 20.10 kN/m^3, respectively.

A comparison between geotechnical index testing results (Proctor and relative density) and gyratory results is made in Table 20 and Table 21. The values represent the percentage of compaction achieved by the gyratory compactor compared to the index tests. The dry unit weight values (displayed in parentheses) were determined at optimum moisture contents.

Table 20: Comparative Analysis of Results for A-3 Soil Compacted at 200 kPa Confinement Pressure

Number of Gyrations & $\gamma_{d(ult)}$ for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (17.45 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (18.39 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (18.47 kN/m^3)
0 Gyrations (15.99 kN/m^3)	91.6%	86.9%	86.6%
75 Gyrations (19.11 kN/m^3)	109.5%	103.9%	103.5%
90 Gyrations (19.19 kN/m^3)	110.0%	104.4%	103.9%
500 Gyrations (19.93 kN/m^3)	114.2%	108.4%	107.9%

Table 21: Comparative Analysis of Results for A-3 Soil Compacted at 600 kPa Confinement Pressure

Number of Gyrations & $\gamma_{d(ult)}$ for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (17.45 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (18.39 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (18.47 kN/m^3)
0 Gyrations (16.73 kN/m^3)	95.9%	91.0%	90.6%
75 Gyrations (19.99 kN/m^3)	114.6%	108.7%	108.2%
90 Gyrations (20.10 kN/m^3)	115.2%	109.3%	108.8%
500 Gyrations (20.95 kN/m^3)	120.1%	113.9%	113.4%

These results indicate that the A-3 soil achieved higher levels of compaction in the gyratory compactor than the geotechnical index tests (Proctor and relative density). At 200 kPa and 600 kPa confinement pressure, gyratory compaction was able to surpass dry unit weights achieved by all of the traditional compaction tests.

Table 20 shows that at 75 gyrations, gyratory compaction achieved 109.5% and 103.9% of the Standard and Modified Proctor dry unit weights, respectively. At 500 gyrations, the same test achieved 114.2% and 108.4% compaction of Standard and Modified Proctor dry unit weights. This *NPD* in gyrations resulted in a 4.7% and 4.5% increase in compaction of Standard and Modified Proctor dry unit weights, respectively. The same comparison can be made in Table 21 between percent gyratory compaction of Standard and Modified Proctor dry unit weights for 75 and 500 gyrations. The *NPD* as a result of increasing the gyrations from 75 to 500 produces an increase of 5.5 and 5.2% compaction of Standard and Modified Proctor dry unit weights, respectively. In general, these percent increases indicate that increasing the number of gyrations is an effective method of increasing the dry unit weight of A-3 soils.

The effects of confinement pressure are determined by comparing Table 20 to Table 21. At 500 gyrations and 200 kPa confinement pressure, gyratory compaction achieved 114.2% and 108.4% compaction of the Standard and Modified Proctor dry unit weights, respectively. At 500 gyrations and 600 kPa confinement pressure, gyratory compaction achieved 120.1% and 113.9% compaction of the Standard and Modified Proctor tests, respectively. The difference between the test at 200 and 600 kPa produces a *NPD* of 5.9% and 5.5%, respectively. These increases are solely due to increased confinement pressures.

The previous paragraphs indicate that both increased confinement pressures and increased gyrations equally affect the degree of gyratory compaction. Approximately 5% increases in the degree of gyratory compaction to Proctor compaction were gained by both increasing the gyrations and confinement pressure.

The effects of the 200 and 600 kPa confinement pressure are directly compared in Figure 22. This figure compares the difference in the 500 gyrations (ultimate gyratory compaction) compaction curves of Figure 20 and Figure 21.

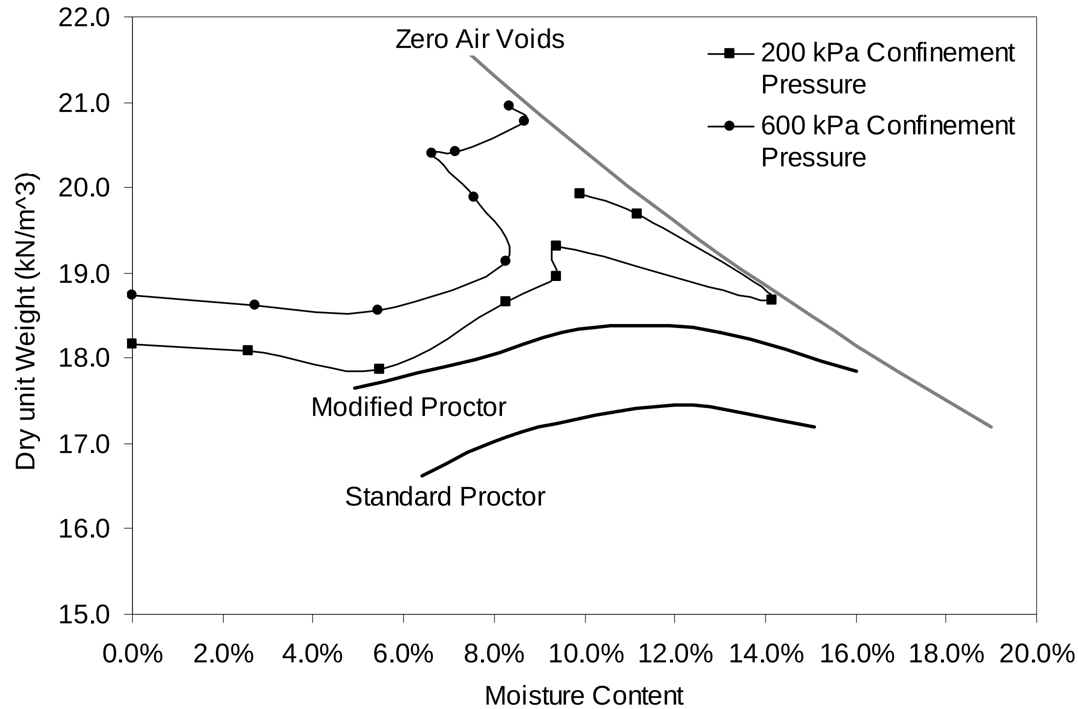

Figure 22: A-3 Compaction Curve for 500 gyrations at 200 & 600 kPa Confinement Pressures

Figure 22 illustrates the effects of confinement pressure. In general, the 600 kPa gyratory curve, which imparts more energy into the soil, achieves higher dry unit weights at lower moisture contents than the 200 kPa gyratory curve. This figure also clearly illustrates the degree of soil compaction occurring in the gyratory compactor. Several of the gyratory data points for both 200 and 600 kPa confinement pressure are near the zero-air voids line. This line represents the absolute compaction that can be achieved for this particular soil and moisture contents, regardless of the compaction technique.

<u>Quantifying Moisture Loss in Free-draining A-3 Soil.</u> Water loss during gyratory compaction in the A-3 soil at 600 kPa confinement pressure was quantified by determining the amount of water lost versus gyration number. To quantify the amount of

water lost during different stages of gyratory compaction, soil samples all having a similar initial moisture content were compacted to increasingly higher gyrations. Moisture content measurements, taken before and after gyratory compaction, were used to quantify moisture loss during compaction. The percent difference (*PD*) in moisture content between the initial and final moisture contents was calculated using Equation 15. The PD values are displayed in Table 22.

$$PD = \frac{w_i - w_f}{w_i} * 100\% \tag{15}$$

where w_i is the initial moisture content and w_f is the final moisture content.

Table 22: Percent Water Loss During Gyratory Compaction of A-3 soil.

Number of Gyrations	Initial Moisture Content (%)	Final Moisture Content (%)	Percent Difference (%)
10	17.8	16.6	6.7
25	18.2	14.0	23.1
50	17.7	12.5	29.5
100	17.0	11.3	33.3
200	17.3	10.7	37.8
350	17.0	9.9	41.6
500	16.4	9.5	42.2

Figure 23 displays the percent difference in moisture content as the number of gyrations increase. The majority of the water loss occurs within the first 100 gyrations; however, some additional water continues to escape throughout the entire test until about 350 gyrations when the water loss rate approaches zero.

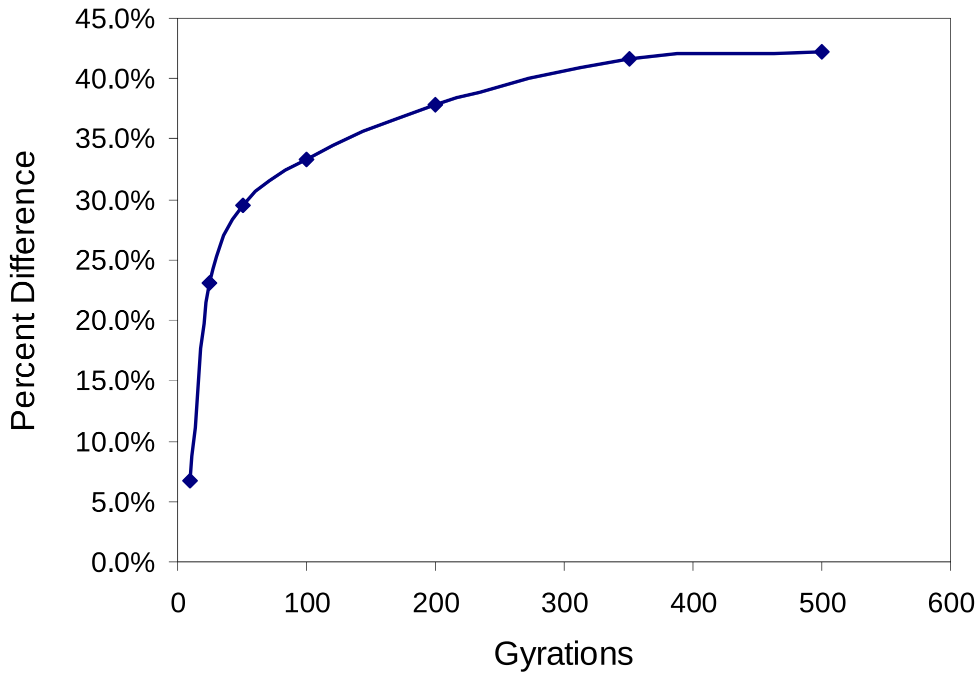

Figure 23: Percent Difference in Moisture Loss during Gyratory Compaction of A-3 soil at 600 kPa.

Knowing what stage of gyratory compaction the water loss occurs at was used to determine which moisture content should be used for calculation of A-3 dry unit weights. The results displayed in Figure 23 indicate the final moisture content would be more representative of the average moisture content of the soil throughout gyratory compaction. The final moisture content was to calculate A-3 dry unit weights throughout this study, unless specifically stated otherwise.

A-4 Soil

Figure 24 and Figure 25 display the UWCC of A-4 soil for confining pressures of 200 and 600 kPa, respectively. Each figure contains multiple tests, at different moisture contents.

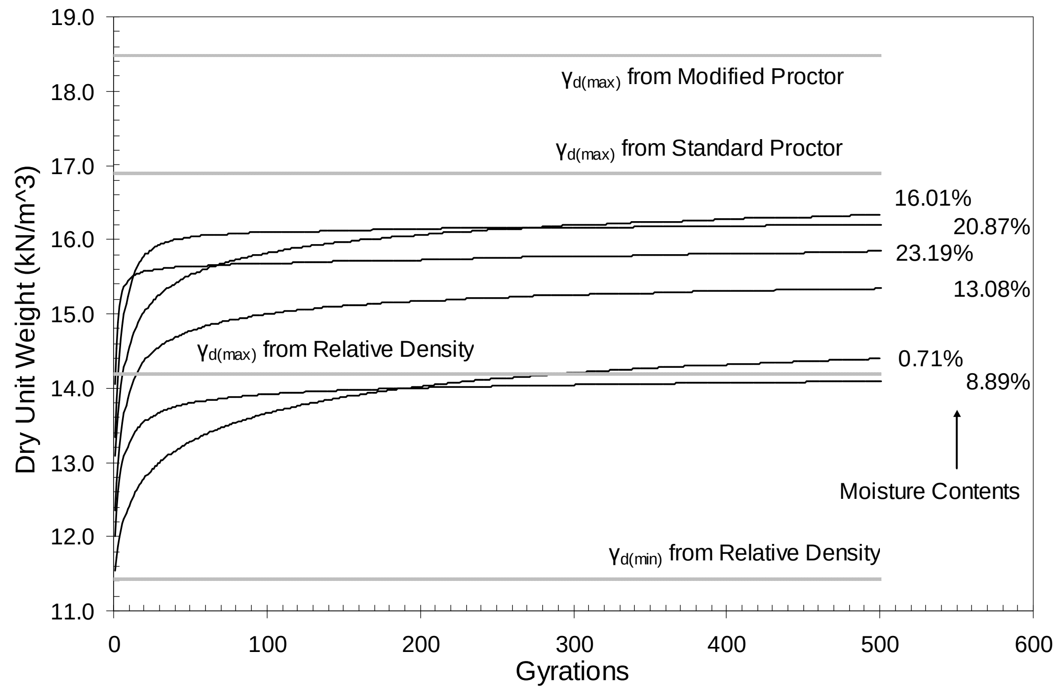

Figure 24: A-4 UWCC Plot for 200 kPa Confinement Pressure and Multiple Moisture Contents

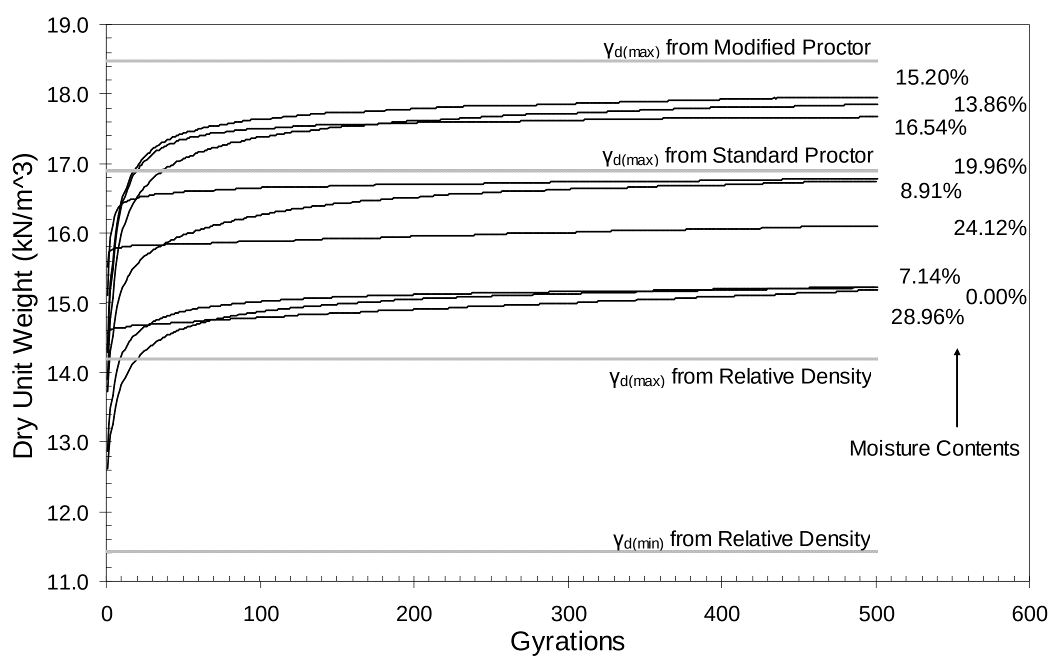

Figure 25: A-4 UWCC Plot for 600 kPa Confinement Pressure at Multiple Moisture Contents

Visual analyses of Figure 24 and Figure 25 reveal that the majority of densification on the A-4 soil occurs within the first 100 gyrations. The figures also reveal that the slope of the gyratory compaction curve is dependant on moisture content of the sample. Low moisture content soils experienced a shallower initial slope than high moisture content soils. Soils with high moisture contents achieved the majority of densification within the first 15 gyrations and then flattened off for the remainder of the test.

Gyratory compaction at 600 kPa confinement pressures, as shown in Figure 25, achieved higher dry unit weights than when compacted at 200 kPa (Figure 24). However, neither of these gyratory compaction efforts produced dry unit weights as high as the 18.5 kN/m^3 Modified Proctor maximum dry unit weight. The effects of confinement pressure on A-4 soil are more apparent in the upcoming compaction curves.

The compaction curves for the A-4 soil are considerably more defined than the two previous soils. This is partially due to the A-4 soil retaining all of the water during gyratory compaction.

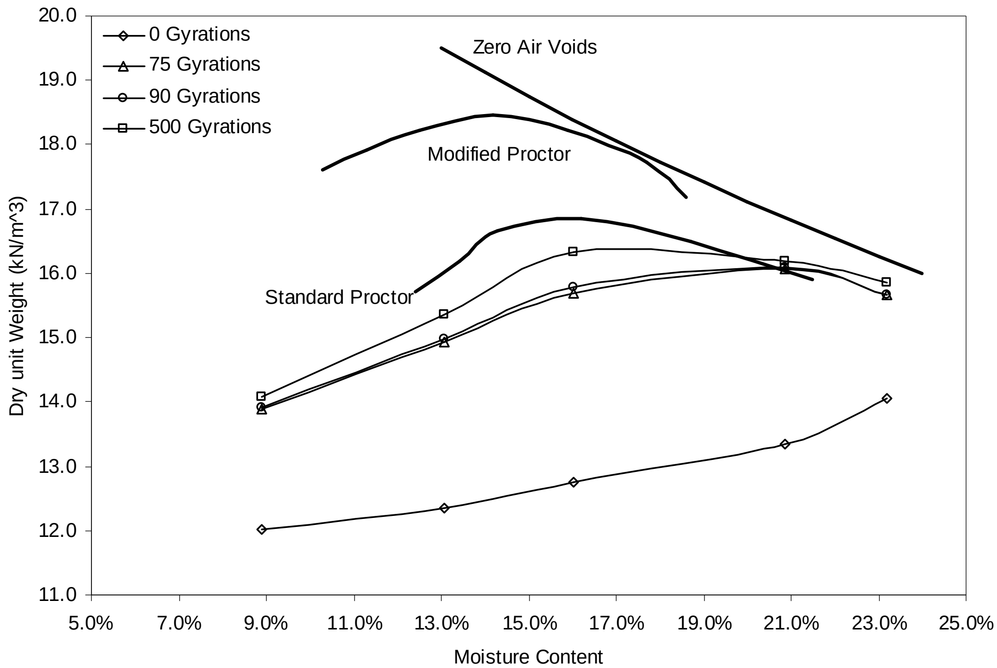

Figure 26: A-4 Compaction Curve for 0, 75, 90, and 500 Gyrations at 200 kPa Confinement Pressure

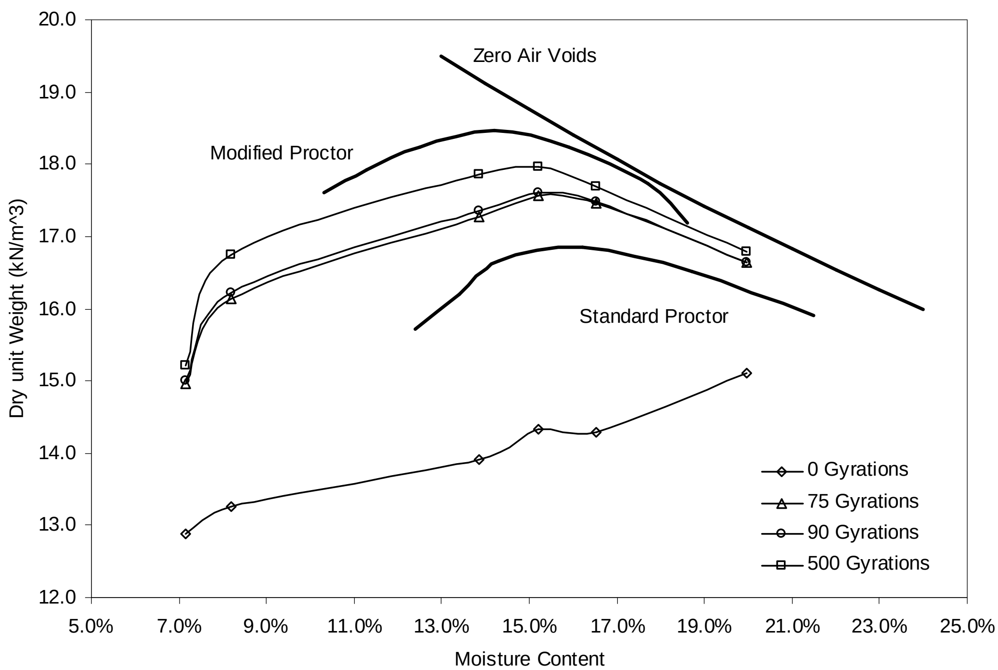

Figure 27: A-4 Compaction Curve for 0, 75, 90, and 500 Gyrations at 600 kPa Confinement Pressure

The zero gyration compaction curves on both Figure 26 and Figure 27 appear to linearly increase in dry unit weight as moisture content increases. The zero gyration curves represent the soil compaction that occurs solely due to confinement pressure. These zero gyration curves do not peak, making it difficult to determine optimum moisture contents. The use of gyrations is required to determine the optimum moisture content and maximum dry unit weight.

Figure 26 and Figure 27 also demonstrate that the number of gyrations to which the sample was compacted influences the maximum dry unit weight. However, for this soil, the number of gyrations the sample was compacted to may not be as significant as the confinement pressure applied to the sample during compaction.

Table 23 and Table 24 show the gyratory compaction that occurs at 0, 75, 90, and 500 gyrations for confining pressures of 200 and 600 kPa, respectively. As before, these tables compare the dry unit weight between the gyratory compactor and Proctor and relative density tests. The values represent the percent compaction achieved by the gyratory compactor compared to the index tests. The gyratory and Proctor dry unit weights (displayed in parentheses) were determined at optimum moisture contents.

Table 23: Comparative Analysis of Results for A-4 Soil Compacted at 200 kPa Confinement Pressure

Number of Gyrations & $\gamma_{d(ult)}$ for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (16.89 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (18.47 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (14.20 kN/m^3)
0 Gyrations (14.06 kN/m^3)	83.2%	76.1%	99.0%
75 Gyrations (16.08 kN/m^3)	95.2%	87.1%	113.2%
90 Gyrations (16.10 kN/m^3)	95.3%	87.2%	113.4%
500 Gyrations (16.34 kN/m^3)	96.7%	88.5%	115.1%

Table 24: Comparative Analysis of Results for A-4 Soil Compacted at 600 kPa Confinement Pressure

Number of Gyrations & $\gamma_{d(ult)}$ for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (16.89 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (18.47 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (14.20 kN/m^3)
0 Gyrations (15.52 kN/m^3)	91.9%	84.0%	109.3%
75 Gyrations (17.56 kN/m^3)	104.0%	95.1%	123.7%
90 Gyrations (17.61 kN/m^3)	104.3%	95.3%	124.0%
500 Gyrations (17.96 kN/m^3)	106.3%	97.2%	126.5%

Results from these tests indicate that the A-4 soil did not achieve the same percentage of densification in the gyratory compactor as the previous two soils (A-1-a & A-3). At 200 kPa confinement pressure, the gyratory compaction curve failed to reach both the Standard and Modified Proctor dry unit weights. At 600 kPa confinement pressure, gyratory compaction was able to reach 106.3% of the Standard Proctor dry unit weight. However, it still failed to reach the Modified Proctor maximum dry unit weight.

As shown in Table 23, increasing the gyrations from 75 to 500 resulted in an *NPD* of 1.5% and 1.4% when comparing gyratory compaction to Standard and Modified Proctor dry unit weights, respectively. In Table 24, increasing the gyrations from 75 to 500 resulted in an *NPD* of 2.3% and 2.1% when comparing gyratory compaction to Standard and Modified Proctor dry unit weights, respectively. These percent increases due to gyrations are minimal compared to the percent increases as a result of confinement pressure.

The effects of confinement pressure can be examined by comparing Table 23 to Table 24. At 500 gyrations, gyratory compaction performed at 200 kPa confinement pressure achieved 96.7% and 88.5% compaction of the Standard and Modified Proctor tests, respectively. At 500 gyrations, gyratory compaction performed at 600 kPa confinement pressure achieved 106.3% and 97.2% compaction of the Standard and Modified Proctor tests, respectively. These *NPD* values (9.6% and 8.7%) are solely due to increased confinement pressures. The results indicate that confinement pressure appears to be the primary parameter controlling the degree of compaction in A-4 soils. A comparison of the maximum dry unit weights achieved at 200 and 600 kPa confinement pressures are shown in Figure 28.

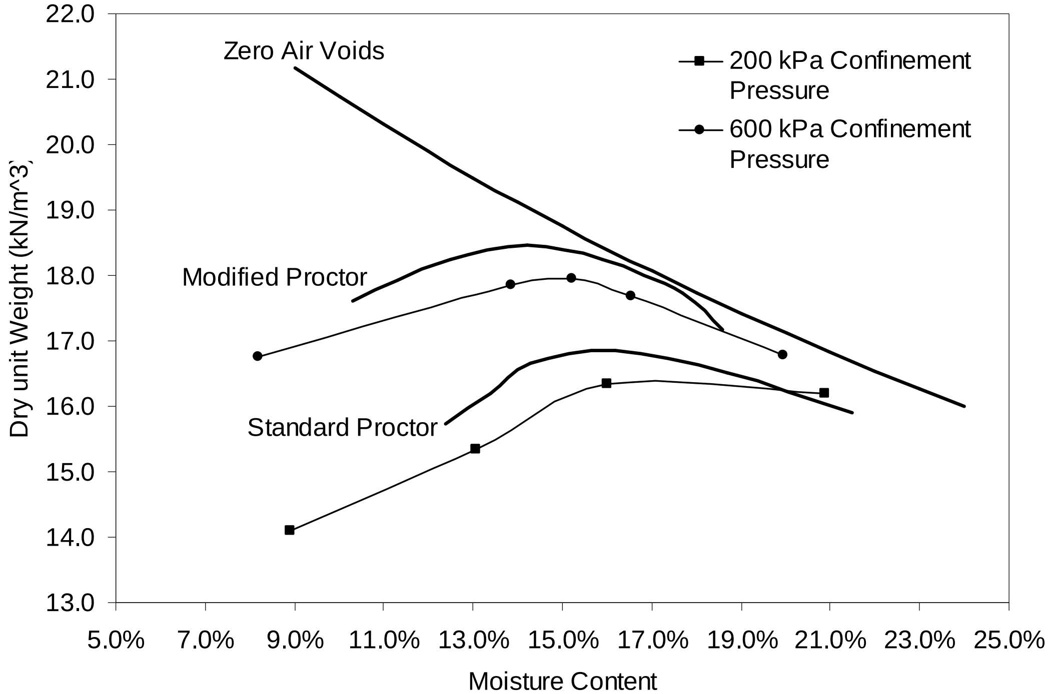

Figure 28: A-4 Compaction Curve for 500 Gyrations at 200 & 600 kPa Confinement Pressures

When compacted using the gyratory compactor, the A-4 soil produced a well defined compaction curve which allowed the optimum moisture content to be readily estimated. The gyratory optimum moisture contents showed similar patterns of decreasing as maximum dry unit weights increased when compared to the trends of Standard and Modified Proctor optimum moisture contents and maximum dry unit weights.

A-7-6 Soil

Figure 29 and Figure 30 show the UWCC plots for A-7-6 soil that were compacted at 200 and 600 kPa confinement pressures, respectively. Each UWCC plot contains multiple tests, at different moisture contents.

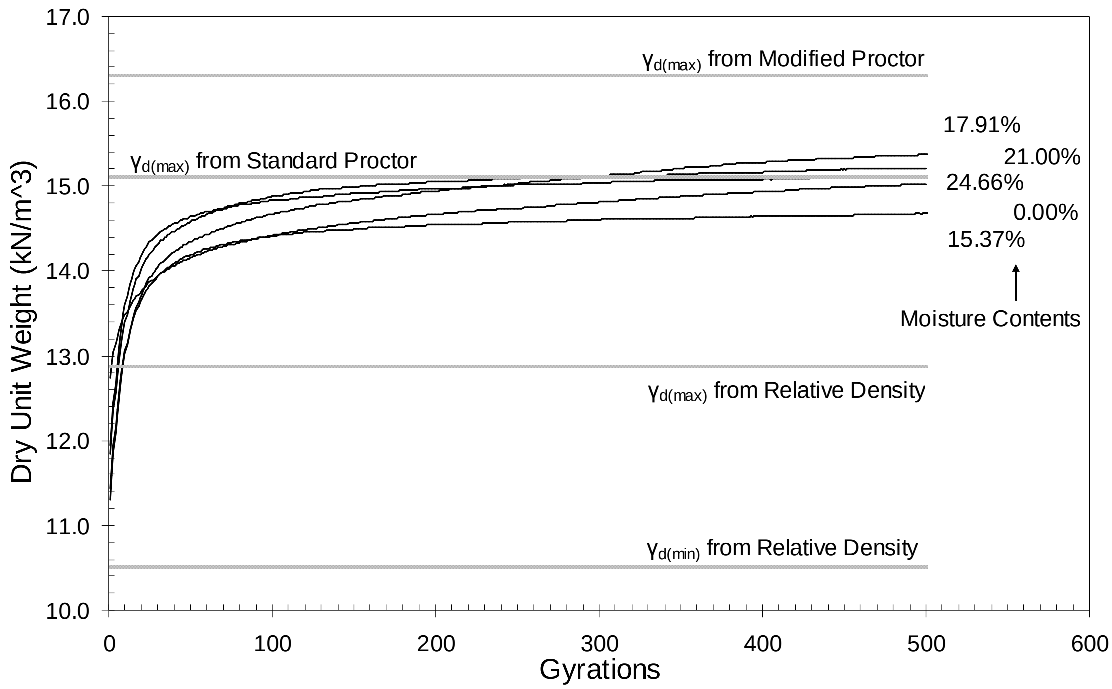

Figure 29: A-7-6 UWCC Plot for 200 kPa Confinement Pressure and Multiple Moisture Contents

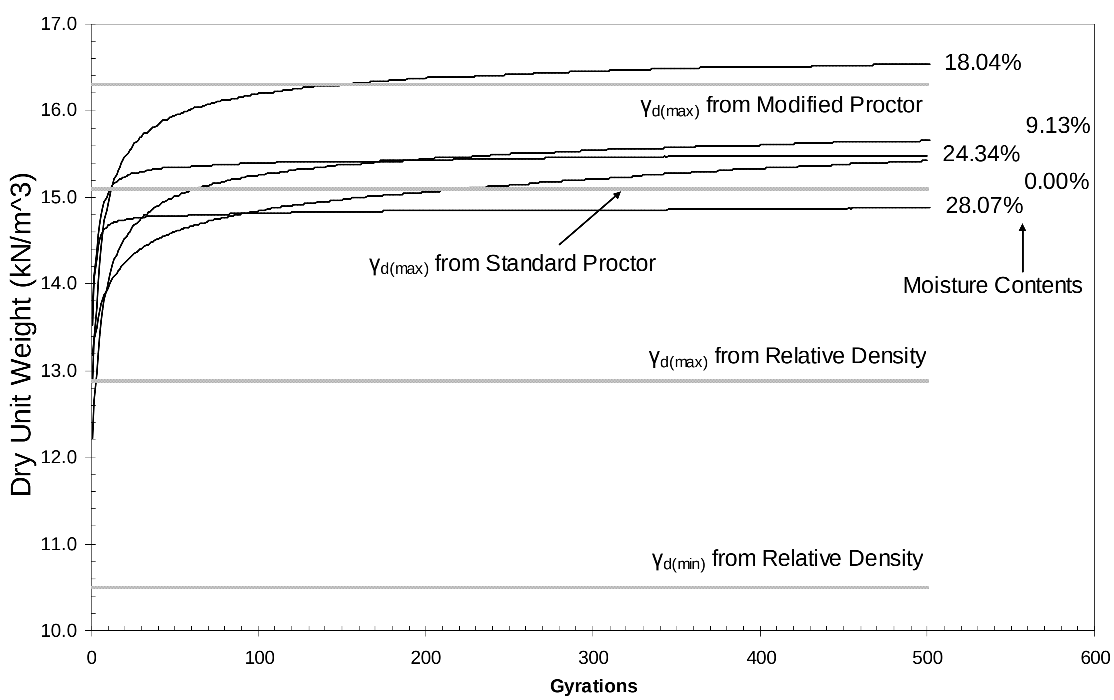

Figure 30: A-7-6 UWCC Plot for 600 kPa Confinement Pressure and Multiple Moisture Contents

The A-7-6 soil showed many of the same gyratory characteristics and trends as the A-4 soil. The majority of compaction achieved using the SGC occurs within the first 100 gyrations. The slopes of the lines representing each test are dependant on the moisture content of that particular test. Tests that were run on the dry side of optimum have a slightly steeper slope from approximately 100 to 500 gyrations. Samples that were tested on wet side of optimum moisture content achieved the majority of densification within the first 15 gyrations. These high moisture samples had a relatively flat slope from 15 to 500 gyrations.

Gyratory compaction performed at 600 kPa confinement pressure achieved higher dry unit weights than the compaction performed at 200 kPa. Only results from tests run at 600 kPa confinement pressures had dry unit weights that matched Modified Proctor dry unit weights. The effects of confinement pressure and number of gyrations are illustrated in Figure 31 and Figure 32.

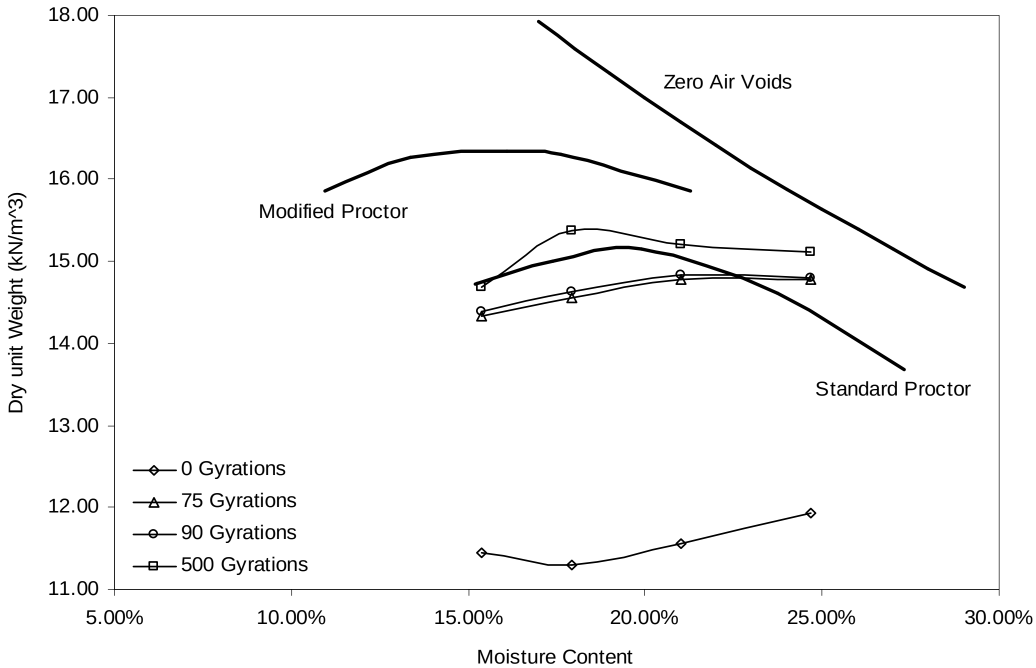

Figure 31: A-7-6 Compaction Curve for 0, 75, 90, and 500 Gyrations at 200 kPa Confinement Pressure

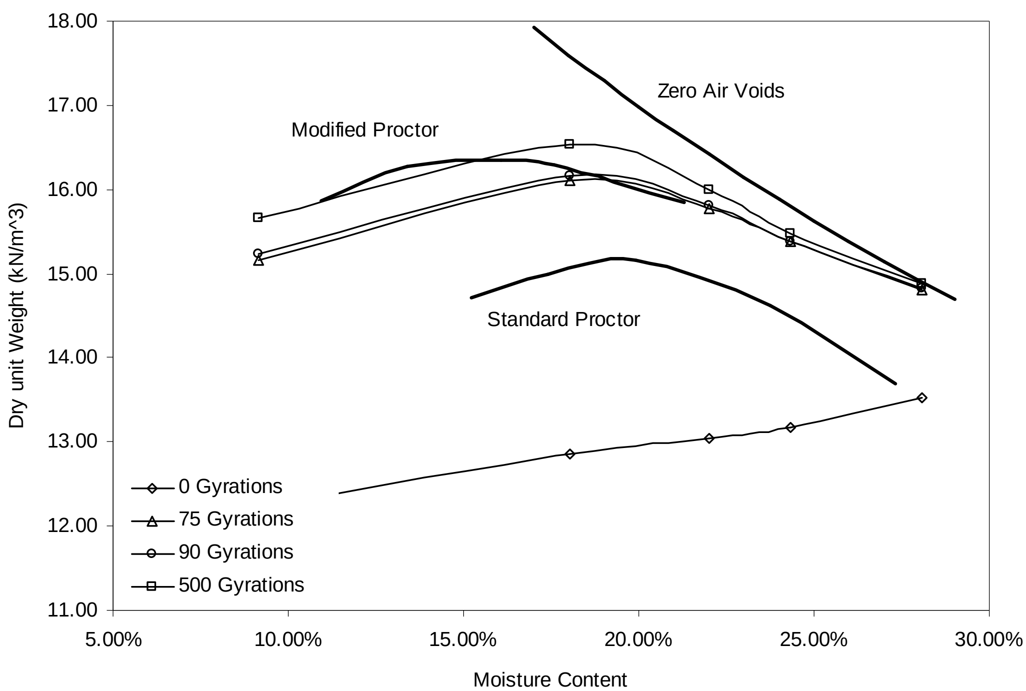

Figure 32: A-7-6 Compaction Curve for 0, 75, 90, and 500 Gyrations at 600 kPa Confinement Pressure

The zero gyration curves on both Figure 31 and Figure 32 linearly increase in dry unit weight as moisture content increases and therefore can not be used to determine optimum moisture contents. This soil requires the sample to be gyrated to determine optimum moisture content and dry unit weight.

Gyratory compaction of A-7-6 soil at a 200 kPa confinement pressure (Figure 31) did not produce compaction curves that were as well defined as compaction curves produced from 600 kPa confinement pressure (Figure 32). This is useful information for future testing to know that the gyratory compaction curves will likely be more defined when compacted at high confining pressures.

Figure 31 and Figure 32 also demonstrate the number of gyrations the sample was compacted influences the maximum dry unit weight. However, for this soil, the number of gyrations the sample was compacted to may not be as significant as the confinement pressure applied to the sample during compaction.

Table 25 and Table 26 show gyratory compaction that occurs at 0, 75, 90, and 500 gyrations for confining pressures of 200 and 600 kPa, respectively. These tables compare gyratory compaction to traditional compaction tests. The values represent the percentage of compaction achieved by the gyratory compactor compared to the index tests. The gyratory and Proctor dry unit weights (displayed in parentheses) were determined at optimum moisture contents.

Table 25: Comparative Analysis of Results for A-7-6 Soil Compacted at 200 kPa Confinement Pressure

Number of Gyrations & $\gamma_{d(max)}$ for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (15.10 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (16.30 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (12.88 kN/m^3)
0 Gyrations (12.44 kN/m^3)	82.4%	76.3%	96.6%
75 Gyrations (14.77 kN/m^3)	97.8%	90.6%	114.7%
90 Gyrations (14.84 kN/m^3)	98.3%	91.0%	115.2%
500 Gyrations (15.38 kN/m^3)	101.9%	94.4%	119.4%

Table 26: Comparative Analysis of Results for A-7-6 Soil Compacted at 600 kPa Confinement Pressure

Number of Gyrations & $\gamma_{d(max)}$ for Gyratory Compaction	$\gamma_{d(max)}$ for Standard Proctor (15.10 kN/m^3)	$\gamma_{d(max)}$ for Modified Proctor (16.30 kN/m^3)	$\gamma_{d(max)}$ for Relative Density (12.88 kN/m^3)
0 Gyrations (13.53 kN/m^3)	89.6%	83.0%	128.9%
75 Gyrations (16.10 kN/m^3)	106.6%	98.8%	153.3%
90 Gyrations (16.16 kN/m^3)	107.0%	99.1%	153.9%
500 Gyrations (16.54 kN/m^3)	109.5%	101.5%	157.5%

Results from these tests indicate that the A-7-6 soil moderately performed in the gyratory compactor compared to the previous three soils (A-1-a, A-3, and A-4). At 200 kPa confinement pressure, the gyratory compaction curve failed to reach the Modified Proctor dry unit weights. However, at 600 kPa confinement pressure, gyratory compaction was able to reach 101.5% of the Modified Proctor dry unit weight at 500 gyrations.

Table 25 shows that at 200 kPa confinement pressure and 75 gyrations, gyratory compaction achieved 97.8% and 90.6% of the Standard and Modified Proctor dry unit weights, respectively. At 200 kPa confinement pressure and 500 gyrations, the same test achieved 101.9% and 94.4% compaction of Standard and Modified Proctor dry unit weights. This increase in gyrations results in an *NPD* of 4.1% and 3.8% of the Standard and Modified Proctor dry unit weights. The same comparison can be made in Table 26 between percent gyratory compaction of Standard and Modified Proctor dry unit weights for 75 and 500 gyrations at 600 kPa confinement pressure. The increase in gyrations from 75 to 500 results in an *NPD* of 2.9% and 2.7% compaction of Standard and Modified Proctor dry unit weights.

The effects of confinement pressure can be examined by comparing Table 25 to Table 26. At 500 gyrations, gyratory compaction performed at 200 kPa confinement pressure achieved 101.9% and 94.4% compaction of the Standard and Modified Proctor dry unit weights, respectively. At 500 gyrations and 600 kPa confinement pressure, gyratory compaction achieved 109.9% and 101.5% compaction of the Standard and Modified Proctor tests, respectively. These *NPDs* (8.0% and 7.1%) are solely due to increased confinement pressures.

The comparisons made between increasing the number of gyrations or confinement pressure indicate that confinement pressure has a larger affect on degree of compaction in

A-7-6 soils. A graphic comparison between the dry unit weights achieved compaction at 200 and 600 kPa confinement pressure is shown in Figure 33.

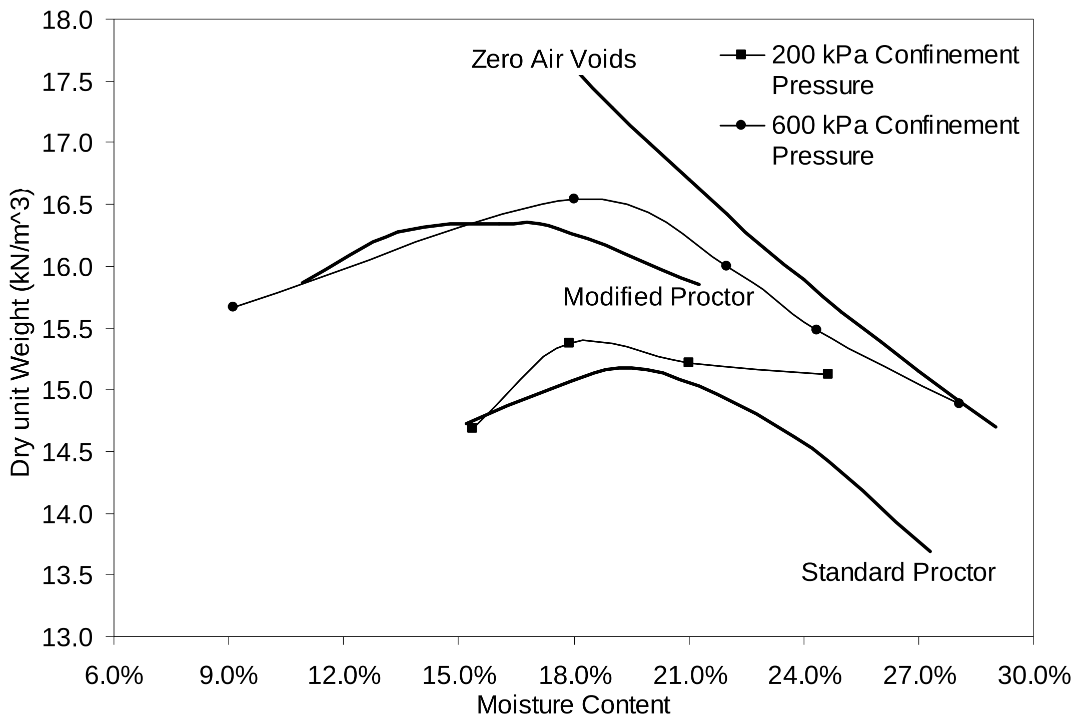

Figure 33: A-7-6 Compaction Curve for 500 Gyrations at 200 & 600 kPa Confinement Pressures

Soil Degradation in the SGC

The literature review revealed that the soil particles may degrade when compacted in the SGC (Collins et al., 1997). The degree of soil degradation depends on the SGC parameters (number of gyrations and confinement pressure) and soil type. Degradation was not the focus of this research; therefore, limited degradation testing was performed. Two granular soils (A-1-a & A-3) were selected to characterize SGC degradation due to their relatively large particle size. Larger particles are more likely to break down and to quantify the degradation. To maximize degradation and show the "worst case scenario", the soil was tested dry (greatest particle friction) at a confinement pressure of 600 kPa and compacted using 500 gyrations. The durability analysis used during this research was performed in accordance to the following procedure:

1) Perform a gradation analysis on the soil prior to gyratory compaction.
2) Compact the soil in the SGC to 500 gyrations at 600 kPa confinement pressure.
3) Perform a gradation analysis on the soil after being gyratory compacted.
4) Graphically compare the two gradation analysis to determine the amount of soil degradation that occurred as a result of gyratory compaction.

Figure 34 and Figure 35 show results from the degradation analysis performed on A-1-a and A-3 soils, respectively. The left curves on the figures represent the gradation of the virgin soil sample. The right curve represents the gradation curve of the same soil sample, after gyratory compaction.

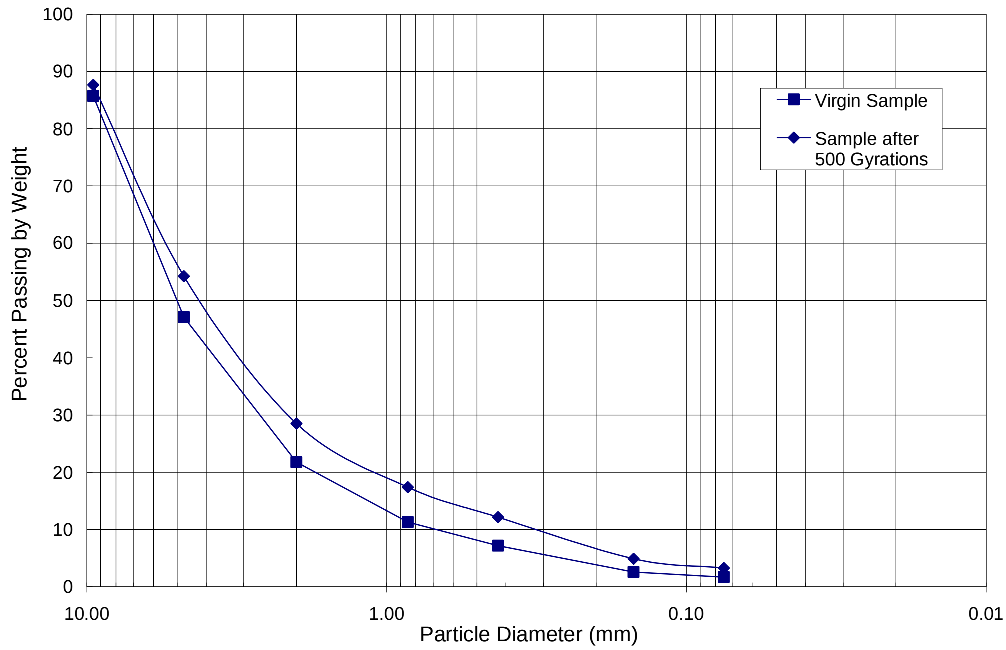

Figure 34: Degradation Analysis of A-1-a Soil Gyratory Compacted to 500 Gyrations at 600 kPa Confinement Pressure

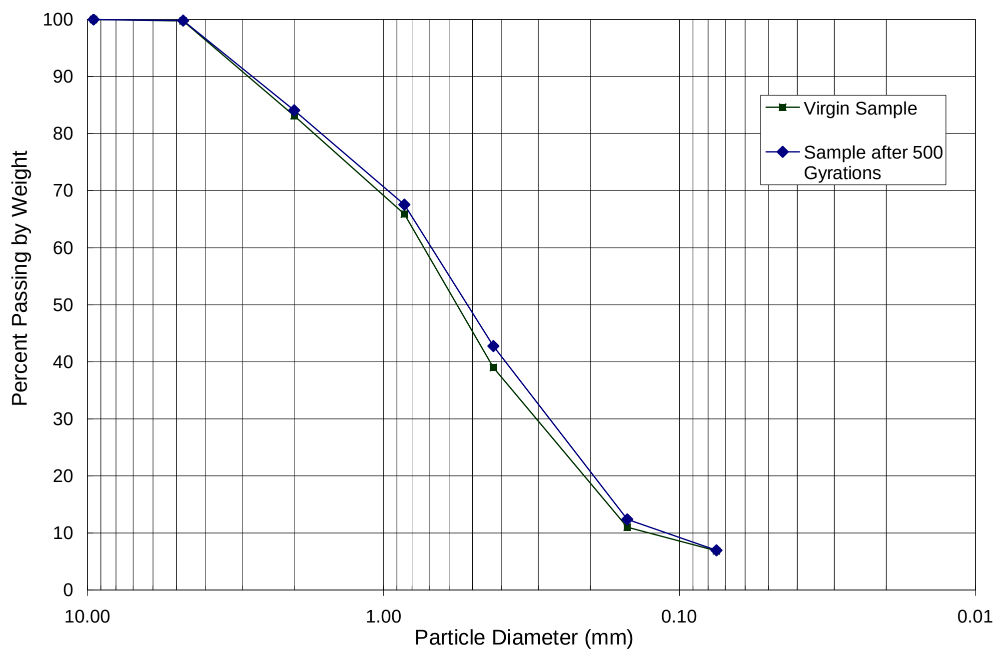

Figure 35: Degradation Analysis A-3 Soil Gyratory Compacted to 500 Gyrations at 600 kPa Confinement pressure

The A-1-a soil showed more degradation than the A-3. This is likely due to the A-1-a having larger soil particles. Large soil particles are prone to experiencing point loads, which can lead to particle break down. The A-3 soil showed very little breakdown. This is likely since this soil has smaller soil particles which can evenly distribute pressures applied by the SGC or because the weaker particles had already degraded or fractured. It also may have to do with the strength of the individual soil particles. It is difficult to determine the exact cause of the degradation.

The largest particle breakdown experienced by the A-1-a soil was approximately a 7% difference in percent passing by weight at the number 10 sieve (2.00 mm). The A-3 soil showed less particle breakdown but still did experience a 4% difference in percent passing by weight at the number 40 sieve (0.425 mm). The significance of this breakdown is unknown. Standardized degradation tests, such as L.A. Abrasion and Micro Deval, were not performed to provide a comparison.

Some soil degradation is expected during both laboratory and field compaction. The SGC was designed to simulate degradation and particle orientation which occurs in HMA during mix production, field compaction, and traffic degradation (Collins et al., 1997). Therefore it is likely that degradation that occurs as a result of the SGC is more representative of field degradation than degradation caused by Proctor tests.

Repeatability

To determine the consistency of SGC soil compaction, repeated tests were performed on each of the soils. The test parameters consisted of using dry soil, a 600 kPa confinement pressure, 1.25° angle of gyration, gyration rate of 30 gyrations per minute, and 500 gyrations.

A Student's t-test was used to determine the number of test replicates needed using Equation 16.

$$n = \left(\frac{t \cdot v}{A} \right)^2 \tag{16}$$

where *n* is the number of specimens (test replicates), *v* is the coefficient of variation of test replicate results (COV = standard deviation/mean), *t* is the value of Student's t for one-sided limits for a 95% probability level as shown in Table 27, and *A* equals 5% which is the value of the allowable variation or error.

Table 27: Values of Student's t for One-Sided Limits and 95% Probability.

Degrees of Freedom (*n*-1)	*t*
1	6.314
2	2.920
3	2.353
4	2.132
5	2.015
6	1.943

As test replicates were performed, an average coefficient of variation (COV) was calculated. As additional tests were performed, the COV was recalculated. Test replicates were stopped when the value of *n* calculated from Equation 16 was less than or equal to the number of replicated tests. The number of test replicates (as calculated by Equation 16) for each soil is displayed in Table 28.

Table 28: Required Number of Test Replicates

Soil	Average *n* based on 2 tests	Average *n* based on 3 tests	Average *n* based on 4 tests
A-1-a	0.410	0.087	-
A-3	0.027	0.094	0.055
A-4	0.025	0.009	-
A-7-6	0.031	0.018	-

Values shown in Table 28 are considerably lower than the number of tests performed; therefore, more than one replicate was not required.

In conclusion, the extremely low *n* values indicate the tests were very repeatable. The low *n* values prove that gyratory compaction tests conducted in the same manner (same number of gyrations, confinement pressure, soil type, soil mass and moisture content) will produce very similar results.

CHAPTER 5

DISCUSION OF RESULTS

Calculation of Gyratory Results

Several approaches were examined to seek a relationship between the gyratory compaction test and other established soil compaction techniques. Each approach was studied to hopefully determine relationships. The author hypothesized that these relationships may help develop a test protocol for gyratory compaction.

A general discussion of the practicality of each approach is discussed in the following sections. Supporting and contradicting statements for each approach are listed when appropriate.

U.S. Army Corps of Engineers Slope Method

The USACE slope method (Equation 7) was used to calculate a gyratory termination point. The termination point was reached when the slope of the compaction curve reached 1 lb/ft^3 increase per 100 gyrations. The termination point served as the point during testing in which gyratory compaction would be stopped and the dry unit weight of the soil would be determined.

Calculation of the USACE slope did not provide consistent or reliable results for the soils compacted in this study. The USACE slope varied considerably depending on soil type, confinement pressure, and moisture content. A trend in termination points was desired that would yield a definitive number of gyrations to compact samples in this study. This trend could not be developed from compaction tests performed during this study; therefore, the USACE method was not used to determine the proper number of gyrations to gyratory compact soil specimens.

10% Air Voids Method

Evaluation of gyratory compaction results in terms of the percent air voids (Equation 8) produced limited results. For this research, a target percent air voids value of 10% or less was desired. Analysis of the soils that were compacted in a moist state produced considerably different results than the dry soils. There was also variability within the moist soils depending on the degree of saturation. Following are some observations based on the 10% air voids criteria:

- The target air voids value of 10% or less was not reached during gyratory compaction of dry soils (A-1-a, A-3, A-4, A-7-6) regardless of confinement pressure or number of gyrations used to compact the sample.
- When compacting water-conditioned soils, cohesive and granular soils on the dry side of optimum did not reach 10% air voids, while granular soils on the high side of optimum often achieved 10% air voids in 10 gyrations or less.
- Granular soils near optimum moisture content and cohesive soils on the wet side of optimum usually did reach 10% air voids. The number of gyrations to achieve 10% air voids varied considerably depending on confinement pressure and moisture content.

The 10% air voids method was used in attempt to determine a proper number of gyrations to compact soils. Analysis of the 10% air voids method indicated this method was extremely sensitive to soil moisture content. This sensitivity produced variability within the analysis and did not allow the four soil types to be uniformly compared. A desired number of gyrations to compact the sample could not be determined from this method.

Relative Compaction

Relative compaction (Equation 11) was used in attempt to provide a direct quantitative correlation between gyratory, Proctor, and vibratory compaction. The procedures differ in compaction method as well as the energy imparted into the soil. For example, the amount of energy imparted into the soil during gyratory compaction will vary, depending on the stiffness of the sample, even if the same gyratory parameters are used. Relative compaction was capable of providing a uniform comparison between the compaction techniques but it failed to provide any additional or new information that traditional compaction curves do not already provide. The relative compaction method was also incapable of determining optimum moisture contents using gyratory compaction.

The degree of relative compaction was found to be dependent on the soil moisture content. The higher the moisture content, the higher the degree of relative compaction achieved. This is due to relative compaction being calculated using the zero-air voids dry unit weight in the denominator. If enough water is added, the sample eventually reaches saturation, which yields a 100% relative compaction based on the definition of relative compaction used in this study. Calculating relative compaction, as shown in Equation 11, is more of an indicator of the degree of saturation rather than the degree of compaction.

A critique of gyratory parameters (confinement pressure and number of gyrations) based on relative compaction failed to produce consistent trends between the four soil types. Relative compaction as calculated in this study was too dependant on moisture content to uniformly compare the effects of the gyratory parameters on the four soils.

Dry Unit Weight

Comparison of the dry unit weights of each compaction method (gyratory, Proctor, and vibratory) proved to be the most practical method of analyzing gyratory results. Maximum dry unit weights and optimum moisture contents of Proctor and gyratory compaction were directly compared by plotting the results of each test on a dry unit weight versus moisture content compaction curve.

This method of comparing dry unit weights is a practical approach of comparing compaction methods; however, it does not take into consideration the compaction energy imparted into the soil, which may vary from test to test. The compaction energy of the Proctor tests are known whereas the compaction energy of the gyratory compactor is unknown.

Gyratory Compaction Energy

Some Superpave gyratory compactors (the Industrial Process Control's Ltd. Servopac SGC and the Pine Instrument Company's AFG1 SGC) are equipped with pressure transducers that are capable of measuring a gyratory shear stress. Gyratory shear stress occurs from the force that is required to rotate the mold carriage which gyrates the mold.

Gyratory shear stress varies depending on the sample stiffness and changes with time during gyratory testing.

The USACE developed an empirical equation to estimate compaction energy based on two forces. The first force is calculated from the confinement pressure applied to the sample throughout compaction. The second force is shear force that is measured from the pressure transducers during compaction.

The Pine Instruments AFGC125X Superpave gyratory compactor used during this study was not equipped with pressure transducers and therefore could not measure gyratory shear stress. Ping et al. (2003) used a Servopac SGC that was capable of estimating compaction energy based on the USACE empirical equation. This study estimated that a gyratory compaction energy of 1,390.67 kJ/m^3 was achieved with an A-3 soil using the parameters listed in Table 29.

Table 29: Comparison of Gyratory Parameters between Ping et al. (2003) and Current Study

	1	2
Study	Ping et al. (2003)*	Current Study
Confinement pressure (kPa)	200	200 to 600
Gyration angle (degrees)	1.25	1.25
Test Length (gyrations)	90	500
Gyration Rate (gyrations / minute)	20	30

* Additional parameters were also tested but these were the parameters used to calculate the compaction energy of 1,390.67 kJ/m^3.

Gyratory parameters used throughout the current study (Column 2 of Table 29) were considerably higher than the Ping et al. (2003) parameters. For example, this study gyrated the sample to 500 gyrations instead of 90 gyrations. Although the compaction energy of this study is unknown; it is likely greater than the 1,390.67 kJ/m^3 determined in the Ping et al. (2005) study. For comparison, the Standard and Modified Proctor tests have compaction energies of 592.7 and 2,693.0 kJ/m^3, respectively.

Gyratory Compaction Variables

The two primary SGC parameters evaluated in this study were confinement pressure and number of gyrations. In attempt to relate gyratory compaction to other laboratory compaction techniques, this study tested multiple combinations of these parameters using varying soil types and moisture contents. Results indicated that the effects of confinement pressure and number of gyrations were dependent on moisture content and soil type.

A general discussion of the trends and characteristics of each of the variables (confinement pressure, number of gyrations, moisture content, and soil type) are provided in the subsequent sections of this chapter. Test results for each soil type are presented in Chapter 4.

Confinement Pressure

Increasing the confining pressure from 200 kPa to 600 kPa generally resulted in an increase in dry unit weight. The degree of this increase depended on the soil type. When compacted to 500 gyrations, the A-1-a soil showed virtually no increase in maximum dry unit weight as a result of increasing confinement pressure from 200 to 600 kPa while soils with smaller particle sizes (A-3, A-4, and A-7-6) showed considerable increase in densification as a result of increasing confinement pressure. The exact percent increase for each soil type with respect to Standard and Modified Proctor are displayed in Table 30 and Table 31 of this report.

There are advantages and disadvantages of using a high confinement pressure for compacting soil specimens. Advantages of using a 600 kPa confinement pressure include:

- The highest dry unit weights for all soil types occurred when using a confinement pressure of 600 kPa and 500 gyrations.
- A 600 kPa confinement pressure was required for the A-4 soil to surpass the Standard Proctor maximum dry unit weight. The A-7-6 soil was only able to surpass the Modified Proctor maximum dry unit weight when gyratory compacted at 600 kPa confinement pressure.
- The testing procedure would be the same as that recommended for HMA. Testing would therefore be consistent with the AASHTO T312 standard.
- For future testing, high confinement pressures will likely allow a lower number of gyrations to be used. This would likely contribute to a lower compaction energy of gyratory testing.
- Compaction curves displaying dry unit weight versus moisture content were more defined at 600 kPa confinement pressure.

Disadvantages of using a 600 kPa confinement pressure include:

- A 600 kPa confinement pressure may be subjecting the laboratory soil samples to pressures and compaction energies that they will never experience in the field; therefore, laboratory compaction may not accurately reflect field compaction.
- A 600 kPa confinement pressure would cause more wear and tear on the SGC than a 200 kPa confinement pressure.
- A 600 kPa confinement pressure would likely cause more particle degradation than a 200 kPa confinement pressure.

In general, the author believes the advantages for using a 600 kPa confinement pressure out weigh the disadvantages.

Number of Gyrations

The number of gyrations a sample is compacted to has a direct effect on the ultimate dry unit weight of the sample. In general, the dry unit weights of granular soils (A-1-a & A-3) increased considerably as gyrations increased. The cohesive soils (A-4 & A-7-6) showed little increase in densification as a result of increasing the gyrations.

As with confinement pressure, there are unique advantages and disadvantages related to the number of gyrations the sample is compacted. The advantages of compacting soils to 500 gyrations, as performed in this study, include:

- The high number of gyrations allows a more thorough understanding of the relationship between dry unit weight and number of gyrations.
- Because sample height is measured after each gyration, changes in dry unit weight can be determined for every gyration.

Disadvantages of compacting soil samples to 500 gyrations include:

- For free-draining soils, increased gyrations results in increased amounts of moisture loss from the sample.
- High numbers of gyrations will result in elevated amounts of aggregate degradation. Degradation testing performed on the A-1-a and A-3 soils (compacted to 500 gyrations) showed a relatively minor amount of degradation. This study did not determine the degradation of samples compacted to varying numbers of gyrations; therefore, it is unknown how much degradation occurs as a result of increasing the gyrations.
- A high number of gyrations will result in high compaction energies for that particular test. Future testing may limit the number of gyrations to stay within a specified compaction energy range.
- A higher number of gyrations will result in an increased amount of wear and tear on the SGC.
- SGCs compact at 30 gyrations per minute; therefore, the more gyrations a sample is compacted, the longer the test takes to run. Experience from this study indicates that the time required to run a test is relatively minor in comparison to the time required to prepare soil samples for compaction.

For experimental research, such as this study, the benefits of compacting to a high number of gyrations out weights the disadvantages. This is primarily due to gaining a thorough understanding of the gyrations versus dry unit weight relationship.

Angle of Gyration

A 1.25 degree gyration angle was used for gyratory compaction throughout this study. This is the AASHTO T312 specified angle of gyration for HMA specimens (AASHTO, 2003). The angle of gyration could not be easily adjusted on the Pine Instruments AFGC125X SGC used in this study and was therefore was not altered from the preset angle of 1.25 degrees.

Soil Moisture Content

Results of gyratory testing of dry soils indicated that three of the four soils tested (A-1-a, A-4, A-7-6) did not achieve the maximum Modified Proctor dry unit weights when compacted to 500 gyrations. For gyratory compaction to be a feasible laboratory compaction method, it must be able to surpass dry unit weights achieved with current laboratory compaction methods (Proctor and relative density) and be relatively able to reach field compaction values.

Gyratory compaction of moist samples was performed to determine if gyratory compaction was capable of achieving dry unit weights that were higher than the maximum Modified Proctor dry unit weights and to determine if optimum moisture contents could be determined using gyratory compaction.

In general, compaction of moist soils produced dry unit weights that matched or surpassed the Modified Proctor maximum dry unit weights. Optimum moisture contents were determined for the cohesive soils. The non-cohesive, granular soils were incapable of retaining water at high moisture contents; therefore, optimum moisture contents could not be determined using the SGC. These same problems also exist in the Proctor tests.

<u>Soil Type</u>

The degree of densification achieved due to confinement pressure, number of gyrations, and moisture content varied for each soil type. In general, the densification rates of cohesive soils were sensitive to moisture content and confinement pressure, while granular soils were more sensitive to the number of gyrations.

Table 30 and Table 31 provide a summary of dry unit weight increases as a result of increased gyratory parameters. The tables summarize values that were presented in detail in Chapter 4. The following subsections discuss the results and trends for each soil type shown in Table 30 and Table 31.

Table 30: Normalized Percent Difference (NPD) in Gyratory Compaction Increases Due to Changes in Selected Parameters with respect to Standard Proctor

	Increase Confinement Pressure from **200** to **600** kPa at 500 Gyrations	Increase Gyrations from **75** to **500** at 200 kPa Confinement Pressure	Increase Gyrations from **75** to **500** at 600 kPa Confinement Pressure
A-1-a	0.4%	6.8%	6.8%
A-3	5.9%	4.7%	5.5%
A-4	9.6%	1.5%	2.3%
A-7-6	8.0%	4.1%	2.9%

Table 31: Normalized Percent Difference (NPD) in Gyratory Compaction Increases Due to Changes in Selected Parameters with respect to Modified Proctor

	Increase Confinement Pressure from **200** to **600** kPa at 500 Gyrations	Increase Gyrations from **75** to **500** at 200 kPa Confinement Pressure	Increase Gyrations from **75** to **500** at 600 kPa Confinement Pressure
A-1-a	0.3%	6.1%	6.0%
A-3	5.5%	4.5%	5.2%
A-4	8.7%	1.4%	2.1%
A-7-6	7.1%	3.8%	2.7%

A-1-a Soil. Table 30 and Table 31 display the percent increases in densification that occur as a result of increased confinement pressure and number of gyrations. These values indicate:

- Increasing the confinement pressure is an ineffective method of increasing densification of A-1-a soils. This was the smallest increase in densification for all the soil types as a result of increasing confining pressure.
- Increasing the number of gyrations is the most effective method of increasing densification in A-1-a soils. Increasing the number of gyrations resulted in the largest percent increase in densification of all the soils.

A-3 Soil. A-3 soil responded well to both increases in confinement pressure and number of gyrations. Increasing the confining pressure did yield a larger percent increase in densification than increasing the number of gyrations. In general, increases in densification can be achieved by either increasing the number of gyrations or increasing the confining pressure, both having approximately the same effect.

A-4 Soil. A-4 soil also responded particularly well to increases in confinement pressure. The A-4 soil achieved the greatest increase in densification as a result of increasing the confinement pressure of all the soils. However, the A-4 soil showed the smallest (of all the soils) increase in densification as a result of increasing the number of gyrations.

A-7-6 Soil. The A-7-6 soil showed similar behaviors as the A-4 soil. An increase in soil densification was gained from increasing the SGC confinement pressure from 200 to 600 kPa. Increasing the gyrations from 75 to 500 gyrations resulted in a relatively small increase in percent compaction.

Comparison to other Gyratory Studies

At the time of this study, Ping et al. (2003) and Fremont (2005) were the only two known studies that used a SGC to compact soil specimens. Details of these studies are discussed in Chapter 2. A comparison of the Ping et al. (2003) study's results and the current study's results are discussed in the subsequent sections. The Fremont (2005) study is currently in progress; therefore, results are unavailable and unpublished. This study was primarily used to help establish methods and gyratory parameters for the current study.

Laboratory Simulation of Field Compaction Characteristics

Ping et al. (2003) performed a study to investigate field and laboratory compaction characteristics of soil and use these characteristics to simulate field compaction in the laboratory. The objective of the second phase of this study was to further investigate the potential of using a Superpave gyratory compactor to simulate field compaction.

The Ping et al. (2003) study is different than the current study in that it measured vertical stresses (load cells placed between soil lifts) and dry unit weights achieved during field compaction. Gyratory compaction was performed to match the field vertical stresses and dry unit weights.

The current study was unable to incorporate field compaction into the gyratory testing scheme. Instead, gyratory compaction dry unit weights were compared to dry unit weights obtained from traditional laboratory compaction techniques.

While the methods of comparing gyratory compaction results differed between the current study and Ping et al. (2003), both evaluated several of the same gyratory parameters. A comparison of the study parameters is shown in Table 32.

Table 32: Comparison of Study Parameters between Ping et al. (2003) and Current Study

	Ping et al. (2003)	Current Study
Confinement Pressure (kPa)	100, 200, 300, 400, & 500	200, 300, 400, 500, & 600
Number of Gyrations	30, 60, & 90	0 - 500
Soil Types	A-2-4 & A-3	A-1-a, A-3, A-4, & A-7-6
Moisture Content	Wet	Dry & Wet

The following numerical list states some general conclusions and recommendations based on results of the current gyratory study. For every conclusion or recommendation of the current study, a supporting or contradicting statement from the Ping et al. (2003) study is listed.

1. Results from the current study indicated that increasing the confinement pressure was an effective means of increasing the soil dry unit weight. Three of the four soils (A-3, A-4, & A-7-6) tested in this study showed increases in dry unit weight as a result of increasing confinement pressure. Ping et al. (2003) also tested an A-3 soil but had a contradicting conclusion in regards to the effect of confinement pressure increases:

   "For the gyratory compaction test, using the vertical stress (confinement pressure) as a means of increasing the dry unit weight was not effective when the vertical stress is more than 200 kPa (Phase I, p. 90)".

2. The current study did not perform field compaction; however, the Ping et al. (2005) concluded:

   "The gyratory test procedure conducted with 200 kPa vertical pressure (confinement pressure), 1.25 degree gyration angle, 90 gyrations, and 20 gyrations per minute showed considerable promise for replicating field compaction characteristics (Phase II, p. 151)".

3. Results from the current study indicate that increasing the number of gyrations a sample is compacted will result in an increased dry unit weight. The effects of increased gyrations were more apparent in the granular soils than the cohesive soils. Ping et al. (2003) stated the following supporting conclusion about increases in dry unit weight as a result of increased gyrations:

   "When the number of gyrations was increased, there was a continuous increase of dry unit weight, which needed to be adjusted to get the desired dry unit weight (Phase II, p. 151)".

4. The current study performed multiple analyses in attempt to develop a standard that would equally evaluate all soil types and moisture contents. These analyses failed to produce a definitive data trend that indicated the

number of gyrations soil samples should be compacted. Continued testing and analysis of multiple soil types should be performed to determine a specified number of gyrations to gyratory compact soil. Ping et al. (2003) also supported this conclusion that additional testing should be performed to develop a common standard for gyratory compaction of soil:

> *"Further investigation needs to be completed in order to develop a standardized test procedure for compacting sandy soils with gyratory compaction (Phase I, p. 91)".*

5. The current gyratory study compacted four soil types (A-1-a, A-3, A-4, and A-7-6). The A-1-a and A-3 are classified as granular soils while the A-4 and A-7-6 are classified as cohesive soils. To the author's knowledge, this is the first study to compact cohesive soils in a gyratory compactor. Densification results of the current study indicated that each soil type reacted differently to the parameters controlling gyratory compaction. To broaden the knowledge of gyratory compaction of soil, the author recommends additional testing of more soil types in the SGC. The following recommendation from Ping et al. (2003) also supports the idea of gyratory testing of additional soil types:

> *"…the experimental program was only focused on a few sites with A-3 fine sand and A-2-4 silty sand soils. The research should be expanded to study the effect of those gyratory variables on clay soils… (Phase II, p. 152)".*

Challenges of Using a SGC to Compact Soil

Several challenges were faced in the laboratory throughout the course of this study. In order for gyratory compaction to be a feasible method of soil compaction, these challenges need long-term, permanent solutions. Details of the challenges encountered and the solutions used in this study are explained in this section.

Anti-Rotation Cog

The gyratory compactor and its respective mold both contain an anti-rotation cog that prevents the gyratory mold from spinning during compaction. Many HMA mixtures do not require the cog to be in place to compact properly (Pine, 1999). Regulations for HMA compaction within Superpave allow the mold to rotate 2 revolutions per 200 gyrations.

Testing during this research caused the anti- rotation cog to shear off the gyratory mold. The cog is attached to the side of the mold with a threaded bolt and a shear pin.

Possible reasons for shearing the cog off include:

- Majority of testing performed during this research compacted the soil samples to 500 gyrations. On average, HMA samples are compacted to 180 gyrations (Roberts et al., 1996). Failure is more likely to occur in a testing regimen that uses an elevated number of gyrations due to increased wear and tear associated with a high number of gyrations.
- It is possible that when soils are tested in the mold a greater torsional force is applied to the anti-rotation cog than when HMA is used. The cog was designed to be used with HMA; therefore, a modified or improved cog may be required for soil testing.

The amount of torsional force applied on the cog is directly related to confinement pressure. At higher confinement pressures, such as the Superpave recommended 600 kPa, larger normal forces create greater friction between the gyratory mold and the SGC which limits the amount the mold can rotate. A considerable portion of the testing performed during this research was performed at low confinement pressures (less than 600 kPa) which likely caused an increased force on the cog. The increased force may have eventually lead to failure.

Formal soil compaction tests have not been performed to compare using or not using the anti-rotation cog. Analysis of tests were run when the cog broke off the mold did not reveal any apparent changes in the compaction results. Visual examination of these tests where the cog broke off revealed the mold appears to rotate approximately 1 revolution per 50 gyrations, twice the acceptable value recommended by Pine (2000).

Some possible solutions to minimize cog failure may include:

- Performing the tests without the cog
- Redesigning a stronger cog

It should be noted that the AFGC125X operational manual states that the anti-rotation cog must be utilized at confinement pressures less than 500 kPa. The affects these solutions may have on the SGC machine or the soil being compacted are unknown. The author is unaware if the cog may be designed to fail at a particular point prior to damaging the SGC.

Compacting Moist Soil Samples

The SGC and the SGC mold were designed to compact HMA samples. When moist soil is compacted in the SGC, the compaction process has the ability to force water out of the sample, which then leaks into the SGC. This is especially true for granular free-draining soils compacted at high moisture contents. A photo showing a moderate amount of water that has accumulated in the SGC during compaction is shown in Figure 36.

Figure 36: Accumulated Water in the bottom of the SGC

The escaping water is caused by the following sequence of events:

1. Moist soil is placed into the mold in a loose state. The void ratio of the sample is large allowing the soil to hold a relatively large amount of water.
2. The soil sample in the SGC begins to compact as the SCG applies a confinement pressure and begins to gyrate. This compaction causes the soil skeleton to compress from a loose state (high void ratio) to a dense state (low void ratio). Soil particles, which are assumed to be non-compressible, cannot

be displaced by compression. Therefore, as the void ratio decreases, the water and air particles are forced out of the sample.

3. The air and water particles are displaced either through gaps around the perimeter of the top or bottom plate of the gyratory mold (as shown in Figure 37).

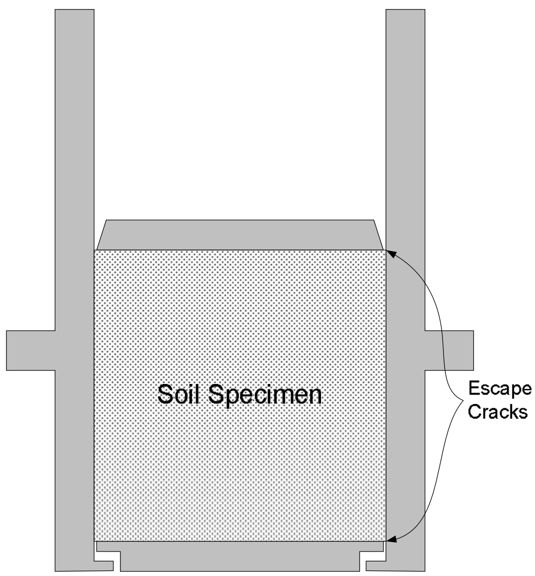

Figure 37: Locations of Water and Air Escape Points in the SGC Mold

As water and soil particles escape the gyratory mold, they pool up inside the SGC. As the SGC gyrates, water and soil particles drain into the undercarriage of the SGC, which houses gears, a drive chain, and sensitive electronic equipment such as the gyration counter. The soil particles are also deposited within cracks between the mold base and mold carriage. These soil deposits accumulate over time and have caused the SGC to lock up.

The majority of problems associated with water leaking out of the mold and into the SGC have occurred while testing the A-3 soil. The A-3 soil is a free-draining cohesionless soil; therefore, water loss during compaction is expected. The granular, A-1-a soil also experienced some water loss at high water contents. The fine grained A-4 and A-7-6 soils did not experience any water loss during gyratory compaction.

The following ideas were addressed during this study in attempt to control excess water during gyratory compaction of soils.

- The current SGC procedure and mold allow water to drain from the mold hence it matches free-draining conditions. If a seal was placed around the top and bottom of the mold, to eliminate water loss, the compaction process would now represent undrained conditions. Undrained conditions would create pore pressures which would eliminate the ability to achieve dry unit weights associated with typical field compaction. For this reason, trapping water within the gyratory mold is not a good idea, unless you are attempting to match compaction in an undrained condition.
- The idea to "vacuum" water as it exited the mold and before it has the chance to enter the SGC was met with partial success. A vacuum device was built that would swing in and vacuum water between passes of the mold carriage arms. This device was created using a small diameter plastic tube connected to a vacuum. A temporary dam was also build around the gyratory mold to contain the water and keep it from dripping into the SGC undercarriage. The mold carriage has three arms and rotates at 30 revolutions per minute; therefore, the

vacuum device had very limited time to actually vacuum the deposited water. The device is also limited to: 1) vacuuming water at only one point while water escapes along the entire circumference of the mold; and 2) vacuuming water that escaped out of the bottom of the gyratory mold, not water that had accumulated on top of the confining plate.

CHAPTER 6

SUMMARY, CONCLUSION, & RECOMMENDATIONS

Summary

This study was initiated by the desire to find a new laboratory soil compaction method that can more accurately represent modern field compaction. The most commonly used laboratory compaction methods are either the Standard or Modified Proctor test. The Standard and Modified Proctor tests were established in the 1930s and 1950s, respectively, and have remained relatively unchanged since then. In the same time frame, field compaction has undergone major advances due to technology advances and equipment size. One particular shortcoming of the Proctor test is that the soil is compacted by an impacting hammer, which is not necessarily representative of typical field compaction motions. Compaction in the field is typically obtained from a combination of kneading, vibration, and static pressures.

This study evaluated the feasibility of using a SGC to compact soil specimens. The SGC was developed in the 1990's as a laboratory compaction device for compacting HMA. Currently, the SGC is the primary laboratory asphalt compaction device used throughout the United States. Gyratory compactors simultaneously use static compression and a shearing action to compact asphalt mixtures. Because the gyratory compactor more closely represents field compaction, and has an established track record of success with asphalt compaction, this project explored the feasibility of using a SGC to obtain maximum dry unit weights and optimum moisture contents of soil. This study explored the methodologies, parameters, variables, and results associated with SGC compaction of soils.

A gyratory testing method was developed based on the current AASHTO T312 compaction method for HMA (AASHTO, 2002) and other recently published studies on gyratory compaction of soil. A suite of laboratory tests were conducted to analyze the primary variables associated with gyratory compaction. These variables include: confinement pressure, number of gyrations, soil type, and moisture content. Based on the review of past studies and limitations of the SGC used during this research, variations from the AASHTO recommended gyration angle and gyration rate were not tested.

Gyratory compaction was performed on four soil types with varying moisture contents. The four soils (A-1-a, A-3, A-4, and A-7-6) used throughout this study were selected to represent a broad range of soils encountered during construction. Geotechnical index testing as well as Standard and Modified Proctor compaction tests were performed on the four soils to determine typical earthwork engineering properties. The maximum dry unit weights achieved through Standard and Modified Proctor compaction were used as a comparison.

To evaluate the degree of soil compaction achieved by the gyratory compactor, the results of gyratory testing were compared to Standard and Modified Proctor results. The initial hypothesis was that gyratory compaction would surpass the dry unit weights achieved using either the Standard or Modified Proctor tests. Multiple analyses of the compaction tests were performed in efforts of determining an optimum number of gyrations and confinement pressure. These methods of analyses include calculation of

USACE slope, percent air voids, relative density, relative compaction, and dry unit weight.

A large number of gyratory compaction tests were performed to evaluate how soil type and gyratory parameters affect soil compaction. Based on the testing conducted in this study, the two most important parameters able to be controlled by the SGC were: 1) confinement pressure and 2) number of gyrations. These parameters were evaluated to determine their effect on dry unit weight of the soil.

Conclusion

Results indicated the effects of confinement pressure and number of gyrations was dependant on soil type and moisture content. In general, increasing the confinement pressure was the most effective method of increasing compaction dry unit weights for fine-grained soils. Increasing the number of gyrations was the most effective method of increasing compaction dry unit weights for non-cohesive, granular soils.

The initial hypothesis that dry unit weights achieved during gyratory compaction would be able to surpass Standard and Modified Proctor maximum dry unit weights was proved true in three of the four soils (A-1-a, A-3, & A-7-6). At maximum gyratory compaction; the A-1-a, A-3, and A-7-6 soils were compacted to 103.2%, 114.2%, and 101.2% of the Modified Proctor maximum dry unit weight. Gyratory compaction of the A-4 soil only reached 96.9% of the maximum Modified Proctor dry unit weight. In general, gyratory compaction proved to be a viable method of soil compaction. This study showed promising future for gyratory compaction of soils.

This study has shown that, in general, gyratory compaction is a feasible method of laboratory soil compaction. Based on this research, the following conclusions are provided:

- Calculation of soil dry unit weights proved to be the most practical method of analyzing and comparing gyratory results to traditional compaction test results. Calculation of other methods such as: USACE slope method; percent air voids; relative compaction; and relative density did not provide uniform comparisons between the different soil types and moisture contents.
- Gyratory compaction was able to surpass Modified Proctor dry unit weights for three of the four soils tested (A-1-a, A-3, A-7-6).
- Increasing the number of test gyrations resulted in higher dry unit weights, especially for granular soils. Calculating dry unit weight for each gyration also allowed a more thorough and complete understanding of the degree of densification occurring per gyration.
- Increasing the confinement pressure resulted in higher dry unit weights for fine grained soils.
- Compaction rates (increase in dry unit weight per gyration) varied depending on soil type and moisture content. In general, cohesive soils obtain most of their densification through confinement pressure and then continue to slowly densify as gyrations continue for the remainder of the compaction process. Granular soils do not achieve the same degree of densification due to the initial confinement pressure but do continue to densify at a high rate for the remainder of the

compaction process. The rates also vary for each soil type depending on moisture content.

- Gyratory compaction shows considerable promise for compacting free-draining soils. Traditionally, accurate maximum dry unit weights for free-draining soils have been difficult to obtain.
- Compaction of free-draining soils at high moisture contents forced water out of the sample and into the SGC. This water also carried and deposited fine soil particles throughout the SGC. The SGC used in this study was incapable of handling/controlling excess water; therefore, frequent cleaning of the SGC was required. A vacuum device was developed to aid in controlling the water but only achieved moderate success.

Recommendations for Continued Research

This study proved gyratory compaction is a feasible method of laboratory soil compaction, especially with granular soils. This section contains ideas and recommendations to further the study of gyratory compaction of soil. Many of these recommendations are based on issues and obstacles encountered during this study.

Gyratory Compaction Parameters

The author recommends using the following SGC parameters during experimental research:

- Gyratory compaction rate of 30 gyrations per minute.
- Gyratory compaction angle of 1.25 degrees.

- Confinement pressure of 600 kPa.
- Highest number of gyrations possible. High numbers of gyration allow a more thorough understanding of the soil densification that occurs during compaction. This should be performed until a reliable trend indicating a realistic number of gyrations can be established using several soil types.

Except the recommended number of gyrations, these parameters are consistent with the AASHTO standards for HMA compaction. Use of the established AASHTO standards may aid in a future standard of gyratory soil compaction.

Method of Analyzing SGC Data

The current study attempted to relate dry unit weights from the SGC to Standard and Modified Proctor and maximum relative density dry unit weights. Ping et al. (2003) attempted to relate SGC dry unit weights to dry unit weights measured in the field. Both studies had some success but failed to establish a definitive relationship or trend by analyzing gyratory compaction dry unit weights.

A method that analyzes the effects of compaction equipment (field compaction and SGC laboratory compaction) on soil structure, stress, and strain was not explored by either of these studies. Calculation and analysis of the soil modulus from the stress-strain data may be a better method of comparing SGC laboratory compacted soil specimens to soils compacted in the field.

Address Moisture Loss in Free-draining Soils

The A-3 free-draining soil tested in this study lost a considerable amount of water during the course of gyratory compaction. Attempts were made during this study to minimize damage to the SGC caused by water escaping from the sample. Additionally, the water loss creates error and uncertainty in calculations. Some recommendations to address water loss include:

- Develop a more reliable device to contain the water as it is forced out of the sample during compaction. This device must capture the water before it enters the SGC.
- Use a newer or different model SGC than the Pine Instruments AFGC125X used throughout the current study. The author has viewed a newer Pine Instruments model (AFGB1) which appears to be designed in a manner that escaping water will not drip on sensitive electronics within the SGC.

Gyratory compaction of the free-draining A-3 soil used in this study showed that gyratory compaction was capable of achieving higher dry unit weights than Proctor and relative density (e_{min}) dry unit weights. If the issue of water loss during gyratory compaction can be solved, the author for sees that gyratory compaction may be a valid compaction method to accurately represent dry unit weights obtained during field compaction.

Testing of Additional Soil Types

This study exclusively focused on four soils classified as: A-1-a, A-3, A-4, and A-7-6. These soils included non-cohesive (sands and gravels) and cohesive (silts and clays) soils.

Gyratory testing of additional samples of all eight AASHTO soil types would provide more insight on the relationship between soil type and the response to gyratory compaction. This would provide a larger data base of soils to critique and analyze.

The author especially recommends additional testing of free-draining soils. Free-draining soils are difficult to compact using conventional laboratory Proctor methods. Laboratory compaction is often incapable of obtaining dry unit weights that are achieved in the field (ASTM standards recommend performing relative density tests rather than Proctor tests on free-draining soils).

Analysis of the Compaction Energy Involved in Gyratory Testing

Several Superpave gyratory compactors are capable of measuring gyratory shear stress. The USACE developed an empirical equation which relates gyratory shear stress to the compaction energy of gyratory compaction. Using a Superpave gyratory compactor that is capable of measuring shear stress; hence, measuring compaction energy may provide a more direct comparison between field and traditional laboratory compaction. The Superpave gyratory compactor used during this study was not capable of measuring shear stress.

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